A Site-Based Study of Durability Indexes for Concrete in Marine Conditions

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DECLARATION

I declare that this dissertation is my own, unaided work. It is being submitted in partial fulfilment for the Degree of Master of Science in Engineering at the University of Cape Town. It has not been submitted before for any degree or examination at any other University.

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ABSTRACT

GENERAL BACKGROUND

This dissertation comprises a site-based investigation into the ease at which durable concrete can be produced, using three extenders and four site-curing methods over four seasons in the Port of East London (Eastern Cape).

GGBS, FA and CSF were selected as extenders as it is well established that these extenders enhance the durability properties of concrete, relative to plain unblended concretes. The test elements modelled two structural elements in the Port viz. a reinforced concrete retaining wall and mass concrete paving slabs. This was to facilitate possible future correlation or further study. For closer correlation, test elements were cast in close proximity of the actual retaining wall and likewise for the slabs.

Site-curing methods selected were as follows:

Walls

- The application of a resin-based pigmented curing compound;
- The retention of timber 20mm plywood shutters;
- The application of a double layer of saturated hessian covered by a greed plastic sheet; and
- No curing.

Slabs

- The application of a resin-based pigmented curing compound;
- The application of a saturated 75mm layer of sand;
- The application of a double layer of saturated hessian covered by a green plastic sheet; and
- No active curing.

The curing methods were selected given their current use in the industry, ease of application and low cost.

Given that the study took place in an uncontrolled environment, over a full year i.e. four seasons. It was necessary to develop a model or system to evaluate the environmental effect on each of the test elements. Fortunately a recent study[10] completed at the University of Cape Town, made it possible to apply the findings to a preliminary environmental characterisation system.

The system, however has limitation with regard to the following aspects:

- The laboratory based study used OPC concrete only and not extenders;
- The temperature and relative humidity ranges used, in the laboratory based study, did not cover the ranges experienced on site; and
- The results were based on 28-day testing and no 120-day testing was undertaken.

Without the development of this system it would have been impossible to evaluate the interaction between the environment and curing and also to place the study in a regional context. By developing an environmental characterisation system for two other regions in South Africa (Cape Town and Johannesburg), it was possible to comment on the relative effect of the environment, in developing the durability indexes, on the study site.

At the outset of the study only 28-day testing was planned. However the preliminary 28-day results appeared to be somewhat anomalous, hence it was decided to repeat the testing at 120-days. This added a new dimension to the investigation, as it was now also possible to comment on the change in durability index with time. The specification governing the manufacture of cements was revised during the study period and resulted in the discontinuation of the cement used at the outset of the study. It was necessary to make use of the closest available "revised" cement product as for the element age this also made it possible to evaluate the effect of change in binder chemistry.

GENERAL CONCLUSIONS

The environmental characterisation system, although unrefined, and subject to the limitations as explained, was found to be a valuable tool. It indicated clearly that East London provided the most favourable environment of the three regions considered. Initially Durban was also considered, but was discarded from the analysis, due to the similarity of the climatic conditions to East London. In other words Durban and East London can be expected to provide a very similar environment for the development of durability properties.

The chloride conductivity results obtained showed sensitivity to binder type, with FA and GGBS concretes yielding better properties than CSF concrete. This confirmed findings of previous studies and the chloride conductivity results also responded to the change in cement manufacture specification.

The water sorptivity results showed sensitivity to curing, reinforcing the findings of prior studies. The results of the environmental analysis are borne out in that very little variation in results is evident between fully cured and uncured results. This is aligned to the findings in terms of the beneficial environment afforded the test elements in East London.

The oxygen permeability index is shown to be more sensitive to the binders that are known to produce a denser concrete pore structure and curing. Once again the results of this investigation reinforce the findings of previous researchers. The importance of compatibility of cement and extender is highlighted in that the CEM I cement produces noticeably poorer properties, than the OPC cement concretes.

The major single finding is the trend of the durability index results improving with time form 28 to 120 days, regardless of curing method. This is somewhat contrary to previous laboratory work, where it was found that within a short period of time that for fully cured samples, durability properties very close to the 28-day results were realised. The question remains whether they continue to improve with time, and the rate at which this would occur. More importantly, at what age does the improvement slow to become negligible?

The benign environment of East London has masked the sensitivity of the site-curing methods. In other words the observation relating to the improvement of the uncured samples with time will in all probability not be repeated in other regions with a harsher climate. It is thus important to view the site-curing efficiency in relation to the environmental rating developed for a particular area or region. Unfortunately in the case of this study the masking effect is so pronounced that it is not possible to comment on the effectiveness of the various site-curing methods. It must be stressed that this does not suggest that curing has no benefit, but rather that the environment and curing interact in developing durability properties.

THE WAY FORWARD

a) The environmental characterisation system requires refinements in that a study similar to the one undertaken by Griesel[10] is required with the following refinements:

- FA, GGBS and CSF concretes must be added;
- The limits of temperature and relative humidity must be expanded to accommodate the full climatic range experienced in South Africa, and also in order to make it possible to distinguish between the effects of temperature and relative humidity; and
- The durability indexes must be determined at a series of element ages to facilitate evaluation of development of properties with time.

b) With the above information it will be possible to refine the system and then to correlate it with real site-based results for various climatic regions in South Africa. Only then will it be possible to gain a fuller understanding of the complex interaction between curing, the environment and various binder interactions.

c) The interaction between cement type and extender requires more investigation. While this study used cement from one source only, a study evaluating the effect of various cements from various sources will indicate the compatibility of extender and cement type in developing acceptable durability properties.

To my wife for her moral support and understanding

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LIST OF ABREVIATIONS AND NOMENCLATURE

GGBS	Ground Granulated Blastfurnace Slag as supplied by Slagment under the brand name of "Slag".
FA	Fly Ash as supplied by Ash Resources under the brand name of "PFA".
CSF	Condensed Silica Fume as supplied by Ash Resources under the brand name of "MB Silica Fume".
OPC	Typical Ordinary Portland Cement manufactured to SABS 471-1971 as supplied by Alpha Cement under the brand name of "Alpha OPC", used in the manufacture of concrete for this project. (Note: this is pre August 1997 and this brand name no longer available from Alpha Cement). In other instances where literature or authors refers to ordinary portland cement (OPC), the same applies, however the source is unknown.
CEM I	CEM I 42,5 manufactured to SABS EN 197 as Supplied by Alpha Cement under the brand name of "Alpha CEM I".
Curing Compound	A pigmented resin-based curing compound manufactured by Sika (PTY) Ltd sold under the trade name of "Sika Anusol 15".
NBRI	National Building Research Institute of South Africa.
CSIR	Council for Scientific and Industrial Research.
FRD	Foundation for Research Development.

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CHAPTER 1

GENERAL INTRODUCTION

With the realisation that concrete as a construction material is less durable than it was thought to be a decade or two ago, large amounts of resources have been expended in attempting to establish the cause of the misconception and development of remedial measures.

The South African approach has been in the development of the "Durability Index" approach as discussed in more detail in Chapter 2. Much work has been done in South Africa to date, but has been mostly laboratory orientated, and has indicated the benefit of cement extenders, wet curing and water/binder ratio on concrete durability. Links have also been made between design life and durability index results and preliminary "target envelopes" for the various index tests have been suggested.

The ultimate aim of all the work in this field is to culminate in a revised specification that can be easily implemented. Bouwer[6] undertook one of the most comprehensive studies to date, based on concrete produced under site conditions. In her project she had no control of the batching, placing or curing process and her aim was to determine if the index approach was sensitive to on site quality control. This project shares a common focus but differs in that the batching, placing and curing are controlled by the author under site conditions using equipment and technology readily available to the industry. The aim is to determine if it is possible to produce good durability indexes on site, and what curing methods are best suited to ensuring good durability. This it is felt will add a practical dimension to the common aim of developing a revised durability specification.

In Chapter 2 a literature review of available literature and work undertaken in this field is presented with the aim of placing this project in context. The experimental details are discussed in Chapter 3, outlining the location of the test sites and the experimental procedures used. Given that the project was undertaken in an uncontrolled environment, one of the crucial requirements is to produce a characterisation system where the effect of the environment can be quantified and used as a basis to compare test data generated. Thus Chapter 4 sets out a characterisation framework used in the analysis of the durability index data. In Chapter 5 the chloride conductivity results are discussed culminating in conclusions relating to site practices that produce acceptable chloride conductivity results.

Water sorptivity and the oxygen permeability index results are discussed in Chapters 6 and 7 respectively with the related conclusions, and in the final chapter broad conclusions and recommendations for future study are presented.

CHAPTER 2

LITERATURE REVIEW

Three durability index tests have been developed recently by South African researchers[1 2 3 4 5] namely the:

- Oxygen permeability index test;
- Water sorptivity index test; and
- Chloride conductivity index test.

Each test measures a different transport property of fluids or ions through the cover layer of concrete. The resistance of the concrete to these transport processes governs the deterioration of the concrete and embedded steel reinforcement and may therefore define the potential durability of concrete. The tests have proved sensitive to durability-related aspects of concrete construction such as material selection, compaction and curing. The tests have been developed and proven in the laboratory, but limited testing has been undertaken on concrete produced on construction sites. The tests are discussed in more detail in 2.10 of this chapter as also chapter 3.

One of the most comprehensive studies to date, based on concrete produced under site conditions using the durability index tests was undertaken by Bouwer[6], for her M.Eng. (Civil) dissertation. She used the durability index tests to assess quality of concrete produced at several different construction sites in the Cape Peninsula area (Western Cape, South Africa). Both site-prepared cubes as well as cores taken on location from the various structures were tested. Concrete placed on the sites was either site-batched or supplied via a ready-mix operation.

The objectives of Bouwer's study were as follows:

- To measure and present durability index results of actual site concrete, and evaluate the influence of construction methods, design parameters and environment on the index values;
- To measure and present durability index results of several batches of ready-mixed concrete and compare them with the site results; and
- To use the results obtained to assess whether the index tests could assist in controlling concrete quality on-site.

Her study and this project share a common focus to provide a database of results and also to expand the current understanding of appropriate measures to ensure durable concrete. Bouwer prepared a detailed review of available literature at the time of publishing her study (late 1997) and, given the similarity between the two projects, it was decided to prepare a summary of her review as a point of departure. This chapter is in two sections; the first section is a summary of the literature review prepared by Bouwer and the second section is an expansion on the summary where more recently available material is added.

In preparing the summary of the literature review prepared by Bouwer it is important to note the following:

- The summary quotes no references.
- Most of the references as listed by Bouwer have been studied by the writer of this thesis and due comment is made regarding the writer's opinion in terms of the accuracy of her interpretation of the references. However at the time of preparing this thesis, the writer was unable to access all the references listed by Bouwer. Hence in the section detailing the reference list, the studied references as also the references not studied by the writer are noted.
- In the summary no diagrams used in Bouwer's review are reproduced.
- The second section uses the numerical reference scheme, referencing new or additional references as studied by the writer.

SECTION 1: SUMMARY OF LITERATURE REVIEW PREPARED BY BOUWER[6] (1997) (ITEMS 2.1 to 2.11)

2.1 INTRODUCTION

This summary of Bouwer's review begins by briefly assessing the existence and enormity of the concrete durability problem not only in South Africa but globally. The next section covers a definition of durability, briefly outlines the characteristics of the cover layer with the associated transport properties and outlines the degradation mechanisms. Following this is a section that explores the major factors that contribute to the current situation, followed by a proposed solution.

2.2 DURABILITY OF REINFORCED CONCRETE

Deterioration of reinforced concrete structures is a problem that has manifested itself on a global scale, within the last fifty years. A large amount of capital is invested annually on repairs and of concern is that the phenomenon is indicating escalated annual growth.

In South Africa, the problem would appear less severe, but durability related problems are being reported with increasing frequency. In a fairly recent survey of marine concrete structures in the Western Cape, South Africa, it was found that many of the structures in a mild coastal exposure climate manifest cracking and spalling within an average of twenty years after construction while structures in a severe exposure climate show similar degradation after about fifteen years on average.

This points to two disconcerting conclusions, firstly that concrete as a construction material is not as durable as it was thought to be and the rapid deterioration of concrete is a fairly recent phenomenon. Research in the past decade has established that the factors that govern durability aspects of concrete differ from those that govern the strength development of concrete; thus clearly some new technology or tools are required to rectify the current alarming trend.

2.3 A DEFINITION FOR THE DURABILITY OF CONCRETE

The latest revision of the South African Standard for design of reinforced concrete considers a concrete element durable if, "when subjected to potentially destructive exposure (other than wear or loading), it protects the embedded metal from corrosion and performs satisfactorily for the lifetime of the structure".

Since the only protection afforded the reinforcement is via a thin skin of surface concrete, or cover concrete, it follows that durability is largely a property of this layer. The durability of reinforced concrete is thus a function of the ability of the cover concrete to resist the ingress of harmful elements. The compressive strength of concrete bears no relation to the performance of the cover in resisting the ingress of deleterious elements.

The rate of transport of any fluid through concrete depends primarily on the pore structure, the transport mechanism involved, and the chemical composition of the cement and the properties of the aggregate.

2.4 THE COVER LAYER OF CONCRETE

2.4.1 THE CHARACTERISTICS OF THE COVER LAYER

2.4.1.1 At Macro Scale

The poorest quality concrete always tends to occur on the surface or cover layer caused by the following three factors.

- The greatest moisture loss occurs in the surface zone;
- the movement of air and moisture out of fresh concrete results in a gradient of water/binder ratio and
- stresses due to loading are more severe at the outer fibres of the members, increasing the probability of micro cracking.

2.4.1.2 At Micro Scale

The two major factors that define the pore structure of concrete are the pore size distribution and the degree of inter-connectivity of the pores. The relationship between these two factors influences the rate of transport of any fluid through the concrete.

2.4.1.2.1 The Pore Size Distribution

Porosity is defined as a volume property of a material, referring to the non-solid component of the material, and decreases from the outer face of the concrete to the core. The size of the pores in cement paste and concrete varies considerably and can be categorized into three groups as indicated in Table 1.

TABLE 1: PORE SIZE IN CEMENT PASTE

DESCRIPTION	TERMINOLOGY	SIZE
COMPACTION VOIDS AND ENTRAINED AIR	MACRO PORES	> 1 μm
CAPILLARY PORES	MACRO PORES	0,01 TO 1 μm
GEL PORES	MICRO PORES	0,001 TO 0,01 μm

Primarily the capillary and compaction voids and entrained air influence the permeation and penetrability. These pores are the principal pathways for the movement of liquid and gaseous phases in concrete and the degree to which the pores are interconnected is one of the determining factors in the rate of deterioration of a reinforced concrete section.

2.4.1.2.2 The Degree of Inter-Connectivity of the Pores

The degree of inter-connectivity of the pores in concrete (more widely known as the penetrability) is the primary factor that controls the extent and rate of the movement of any fluids or gases into the concrete. This is thus the property of concrete that is one of the main factors in controlling the deterioration of the concrete.

Microcracks between the aggregate and cement paste, and between the reinforcement and the cement paste, result in the penetrability of concrete being greater than that of the corresponding cement paste of well-cured concrete. The presence and distribution of these discontinuities in the pore microstructure of the concrete determine the penetrability of a concrete element. This property affects not only the extent of concrete deterioration but also the rate.

2.4.2 THE TRANSPORT PROPERTIES OF THE COVER LAYER OF CONCRETE

Bouwer's review defined common terminology relating to the transport properties of the cover layer of concrete and also the movement of molecules through the concrete, in some detail. The author has selected to omit the detail but wishes to stress the following important detail: The transport or movement of molecules through concrete is a process of complex interaction between both the characteristics of the cover concrete and the environment to which the element is subjected.

2.5 DETERIORATION MECHANISMS OF REINFORCED CONCRETE

Bouwer[6] focused on this section of her review in great detail and expanded primarily on chemical deterioration mechanisms describing the influence of various factors on the process. This author has selected to omit the detail but wishes to focus on the influence of chloride ions on the chemical deterioration mechanism, given the location and focus of this project, in East London.

2.5.1 CORROSION OF REINFORCEMENT

Given the consensus that the corrosion of reinforcement is believed to be the major cause of deterioration of reinforced and prestressed concrete structures in the marine environment, the author wishes to highlight briefly some important factors of the corrosion process.

2.5.1.1 General

Corrosion of reinforcement in concrete is an electrochemical process that occurs when certain conditions are met. Normally, the reinforcement is protected against corrosion by the impermeability and alkalinity of the concrete, resulting in passivation. Passivation is the process in which the reinforcing is coated by stable free reaction products (ferric oxide), shortly after placing of the concrete, and protects the reinforcing from corrosion.

The alkalinity of the cement paste adjacent to the steel can become reduced due to the ingress of deleterious gases or ions reacting with the hydration products. The lower pH of the surrounding pore fluid can then cause depassivation of the reinforcement and reinforcing will then be available to react in the corrosion process.

2.5.1.2 The Corrosion Process

Once the passivity of the steel is destroyed, the corrosion process can start. Two different types of corrosion can be distinguished, normal corrosion and pitting corrosion.

2.5.1.2.1 Normal Corrosion

Corrosion of steel in concrete is an electrochemical process where potential differences result in the formation of anodic and cathodic areas along the surfaces of a reinforcing bar. Various factors can result in the development of an electrochemical potential difference in concrete.

Oxidation takes place at the anodic site and the liberated electrons move to the cathodic site and the oxidised iron goes into solution in the electrolyte. Air and water penetrate the concrete in the region of the cathodic site and react with the free electrons to form hydroxyl ions, which are transported via the electrolyte to the anode, where they react with the oxidised iron.

The product of this reaction is called rust, and can have up to seven times the volume of the original material. This together with expansive hydraulic pressures results in tensile stresses being generated in the concrete, which cause cracking when the tensile capacity of the concrete is exceeded.

For the above reaction to occur the following conditions must be met:

- The passivity of the reinforcing must be destroyed;
- To facilitate the development of an anodic and cathodic site, a potential difference must exist on the surface of the reinforcing;
- Water must be available to form an electrolytic link between the anodic and the cathodic sites;
- Oxygen must be present at the cathode; and
- To facilitate the flow of electrons from the anode to the cathode, the electrical resistivity of the concrete must be sufficiently low.

If the ratio of the cathodic area to anodic area (A_c/A_a) is greater than 100 the density of the galvanic current will be very high resulting in rapid corrosion.

2.5.1.2.2 Pitting Corrosion

Pitting corrosion differs from normal corrosion in that a very small localized anodic area is developed by ingress of chloride ions, relative to a larger cathodic area. The effect of the large A_c/A_a ratio results in severe localized pitting corrosion. The chloride ions act as a catalyst in the pit accelerating the corrosion process.

2.5.2 THE INFLUENCE OF CHLORIDE IONS

2.5.2.1 The Ingress of Chlorides into Concrete

Chlorides can enter concrete either via contaminants or admixtures in the concrete mix, de-icing salts (used to keep roads ice-free in cold climates), or seawater. Given the location and focus of this project the latter is of interest only, in this case. The ingress of chloride ions into concrete is primarily a function of the penetrability (the degree of interconnectivity of pores or paths) of the cover layer and the presence of a transport medium i.e. water.

2.5.2.2 The Action of Chlorides

Chlorides can be physically bound by being adsorbed onto the pore surface inside the concrete or chemically bound by reaction with the hydration products. The amount of chlorides that can be chemically bound is dependent not only on the cement type but also the chemical composition of the cement and the temperature and relative humidity of the environment.

When the chloride ion concentration exceeds 4 mg/ℓ to 6 mg/ℓ the electrical potential at the steel surface changes from positive to negative, the protective film surrounding the reinforcing steel becomes permeable and unstable, and the underlying metal is depassivated. When the molar ratio of the percentage of free or unbound chloride ions to percentage of inhibitive (OH^-) ions is more than 0,6, the protective film will also be destroyed, even when the pH is above 11,5. When chloride ions reach the protective film in the correct concentration, they either convert insoluble iron oxide to soluble iron chloride or otherwise become included in the oxygen layer in a way that it becomes permeable to gases and ions.

The soluble chloride salts can act as a strong electrolyte which leads to the activation of the metal. When the protective film is destroyed, the chloride ions start to dissolve small areas of the reinforcement, resulting in a severe type of pitting corrosion. The chloride ions act as a catalyst in the pit, accelerating the dissolution of iron in the anodically active pit. The region of pitting corrosion extends partly over the region of iron passivity in the system iron-water. The extent of pitting corrosion depends on the chloride concentration. If the latter is below the critical level, no pitting develops and steel is in the region of passivity. The higher the chloride concentration, the more intense the pitting. With the concentration constant, the corrosion will increase with temperature.

When large amounts of chlorides are present, concrete tends to hold more moisture, lowering the electrical resistivity of the matrix and increasing the risk of corrosion. Chloride ions also introduce a source of variation of electrical potential along the reinforcing steel, thus leading to the formation of concentration cells.

2.6 FACTORS INFLUENCING THE DURABILITY OF CONCRETE

2.6.1 CEMENT TYPE

The cementitious material used both chemically and physically affects the durability of concrete structures. The use of blended cements has become more widely accepted, given the beneficial effect on the durability properties of concrete and also a wider realization for the need to conserve energy and resources.

2.6.1.1 The Effect of Cement Type on the Penetrability of Concrete

As mentioned in 2.4.1.2.2 of this chapter the penetrability of concert is a term used to describe the inter-connectivity of pores in the concrete matrix. In well-cured concrete the use of cement extenders can reduce the concrete's penetrability. The chemical composition of ordinary portland (OPC) cement has little effect on the penetrability of hardened cement paste to the ingress of chloride ions, while the use of granulated ground blastfurnace slag (GGBS) or fly ash (FA) has been shown to decrease the penetrability of concrete several orders of magnitude relative to OPC. In addition to this the pozzolanic reactions between free lime and cement extenders form hydrates that block or close pores or "flow paths" in the concrete.

GGBS (a latent hydraulic material) reacts with water, however very slowly, but when blended with portland cement the reaction is accelerated. The GGBS also consumes free lime released by the hydration of portland cement, which is incorporated into the cement gel.

FA (a pozzolanic material) acts at early stages as an inert fine aggregate reducing the water demand and accelerating the hydration process, when blended with portland cement. Later in the reaction, it reacts with water and hydroxides released by the hydration of portland cement and itself hydrates which fills the pores of the concrete matrix.

2.6.1.2 The Effect of Cement Type on the Chloride Resistance of Concrete

The ingress of chlorides into concrete can be restricted by the physical pore structure of the concrete or by chlorides becoming chemically bound by the reaction products of the hydration process.

Well-cured blended cement concrete is less permeable than normal OPC concrete, and thus has a greater resistance to the ingress of chlorides. GGBS concretes have been shown to resist the ingress of chlorides more successfully than FA concretes, which in turn are more successful, than "unextended" concretes.

The hardened cement paste of GGBS concrete has the ability to chemically bind substantial amounts of chloride ions, thus interrupting the concentration gradient needed for diffusion. FA concretes exhibit a lesser ability to bind chloride ions, but greater than "unextended" concretes.

2.6.2 WATER/BINDER RATIO

The ratio of water to binder is one of the primary determinants of the potential durability of concrete, achievable only if good curing and compaction practices are applied. Broadly the penetrability of concrete is dependent on the degree of hydration of the concrete, and reduces with degree of hydration (should no water be lost to evaporation). For a lower water/binder ratio, more binder is available to react with the water and the sooner is the point reached that the concrete matrix penetrability is such that water loss is negligible. Therefore, the lower the water/binder ratio, and the higher the degree of hydration, the lower the penetrability of the concrete.

2.6.3 AGGREGATE

Aggregate type and size both influence the potential durability of concrete.

2.6.3.1 Aggregate Type

Relative to course aggregate, limestone and dolomite may result in a better bond to cement paste than quartz, feldspar or other aggregates containing mica. It has been suggested that aggregates should be carefully selected to ensure compatibility of thermal expansion properties between the aggregate and cement paste, to minimize cracking due to differential expansion or contraction.

2.6.3.2 Aggregate Size

Due to variations in temperature and relative humidity concrete undergoes dimensional changes and studies have shown that larger aggregates offer more local restraint and induce more microcracking than smaller aggregate. It has also been shown that the coefficient of permeability increases with aggregate size for a given water/binder ratio.

2.6.4 COVER

This is considered by many researchers to be the single most important factor concerning concrete durability. As mentioned previously in this chapter, it is this relatively thin skin that protects the reinforcing from the action of harmful agents. It is thus crucial that the cover layer is of sufficient thickness and quality to ensure protection to the reinforcing.

The advantages of a moderately thick cover cannot be overstated and it has been proposed by researchers that this factor alone (if adhered to) could greatly improve the durability of concrete structures.

2.6.5 CURING

Curing can be defined as the process of maintaining a satisfactory moisture content and temperature in the concrete in the period immediately following placement so that hydration may continue until the permeability and strength is developed. Curing serves primarily a durability function in that it directly affects the quality of the cover layer of concrete.

During the hydration process the compounds of cement react with water and are bound together to form concrete, and as the reaction continues the products are further deposited in the pores of the concrete reducing the permeability and penetrability of the concrete. The hydration process is dependent on the availability of water and it is thus crucial to prevent premature drying of the concrete. This not only stops the hydration process but can also block capillaries in the concrete making it difficult to get water back into the concrete. If on the other hand water is maintained in the concrete, the hydration will continue to reduce the penetrability of the concrete.

Research has shown that initial moist curing of concrete has a more important effect on the sorptivity than the strength, where sorptivity can be defined as the rate of movement of a fluid into concrete due to capillary suction. Blended cements hydrate slower than unblended cements, and thus are more sensitive to the duration of curing. It has also been shown that as the concrete strength grade increases the rate of evaporation of moisture from the concrete decreases and thus these concretes are less sensitive to variations in curing regimes. Thicker sections are less affected by curing for the same reason.

Several different types of curing are used in practice, from covering members with a plastic sheeting to spraying with a curing compound or retaining the formwork for a few days. In general water-retaining curing methods are less effective than water-added curing methods, but the latter is very seldom practical.

2.6.6 COMPACTION

Several researchers have recognized the importance of proper compaction to ensure dense packing of the concrete by eliminating the entrapped air. This not only reduces the penetrability of the concrete but also ensures adequate internal bonding of the constituents of the concrete.

Insufficient compaction can lead to relatively large entrapped air inclusions in low slump concrete (up to 30 mm in diameter) which result in concrete of reduced density and strength. In moderate to high slump concrete insufficient compaction can lead to smaller bodies of entrapped air at the surfaces cast against formwork, which reduce cover and yields poor visual appearance.

Excessive compaction can cause segregation of the concrete and in low slump concretes will result in a lower content of coarse aggregate in the top 10 mm to 20 mm of an element. In moderate to high slump concrete excessive compaction will lead to settling of the coarse aggregates which results in microbleeding of the paste.

2.6.7 ENVIRONMENTAL EFFECTS

For deleterious processes to develop in concrete, interactions are required between the material in the structure and the environment. Of decisive influence is the local climate within meters, or the microclimate within millimeters of the structure, and the conditions around buried or submerged parts of the structure.

The influence of any environment on concrete can be broadly divided into three stages. Stage one is the environmental conditions soon after casting of concrete and these will have a dominant effect on the curing requirements of the structure.

The second stage comprises loading and weather effects such as cycles of wetting and drying as well as heating and cooling. These can facilitate the propagation of micro cracks until they become continuous. Once this happens the permeability of the concrete increases greatly which leads to the beginning of the third stage.

In the third stage, water, oxygen, carbon dioxide and acidic ions are able to penetrate easily into concrete. The presence of these elements can lead to the deterioration of the concrete and reinforcement and can lead to further dramatic increases in permeability of the concrete.

2.6.7.1 Temperature

Increase in the ambient temperature will increase the rate of penetration of carbon dioxide, chloride ions or other aggressive elements into concrete, while it will also increase the rate of evaporation of water from the pores of the concrete. Once the aggressive substances have entered the concrete chemical reactions will be accelerated by the increase in temperature.

2.6.7.2 Relative Humidity

The relative humidity influences the rate at which concrete loses water by evaporation and the amount of water in the concrete will determine the deterioration process that will take place. At very low relative humidities the evaporation rate of the concrete is controlled by the temperature, and elevated temperatures can lead to an increase in the moisture gradient between the concrete and the surface in contact with the air and thus lead to a rapid loss of moisture from the concrete.

2.7 PROBLEMS RELATED TO ACHIEVING CONCRETE DURABILITY

2.7.1 THE DEVELOPMENT OF CONCRETE TECHNOLOGY

Researchers have indicated that in the last fifty years construction techniques have changed in that the primary focus is now on speed of construction. To accommodate this trend it has become common practice to make use of admixtures to reduce the striking times of formwork. Coupled with this is a change in cement manufacture specification, resulting in chemical changes to the material (increase of the C_3S content) and also a increase in fineness. These manufacturing changes have resulted in modern concretes requiring less binder at higher water/binder ratios to achieve the same 28-day compressive strength of concretes than fifty years ago. It is also felt that when a new material or technology offers a certain advantage, it is incorporated into practice immediately without an extended trial period.

The "common sense" approach of the past has been abandoned in favour of the practice of designing for strength alone by using relationship of water/binder ratio versus strength. The result is that many concrete structures are being constructed of highly permeable materials that show signs of durability-related problems very early in their design lifespan.

2.7.2 THE CUBE COMPRESSIVE STRENGTH OF CONCRETE

Researchers believe that many engineers are under a misconception that the concrete cube compressive strength test is a reliable indicator of the durability of the concrete in a structure. The cube test is a bulk property index test and does not exhibit sufficient sensitivity to curing or indicate the quality of the cover layer of the concrete.

2.7.3 CURING

Although curing is crucial to ensuring durable concrete, it has been shown that on most construction sites curing procedures are not adhered to, or if implemented are done so without due care. In an extensive survey in the United States of America, it was shown that approximately 75% of the concrete used in non-residential construction was either not cured at all or not cured to specification. Apart from this there exists little or no quantitative data on the effectiveness of the various site-curing techniques, making it even more difficult to evaluate their suitability.

2.7.4 QUALITY CONTROL

Although it is possible to produce durable concrete under controlled conditions, it has still to be proven that this also applies for concrete in actual structures. It is the experience from several international structures that the properties of the concrete in place differ from the properties determined in the laboratory. The reason for this can be that the current quality control systems rely on small samples prepared independently and subjected to tests in laboratories. The samples are not necessarily representative of the placed concrete.

2.8 INADEQUECIES OF CURRENT SPECIFICATIONS FOR ACHIEVING DURABLE CONCRETE

2.8.1 CURRENT PRACTICE

In the latest revision of the current standard for concrete practice in South Africa, the following durability related specifications are given:

- the minimum thickness of the concrete cover; however no distinction is made between binder types or extender blends;
- maximum water/binder ratios;
- minimum binder content;
- minimum allowable chloride content; and
- concrete grade.

The South African code acknowledges that one of the main characteristics that enhance the durability of any concrete is its impermeability. It points out that the impermeability of the concrete depends on the maximum water/binder ratio, proper compaction and adequate curing practices. The code indicates that the concrete must be cured for a minimum of 7 days after casting to prevent "excessive" moisture loss. While the code highlights the importance of the factors as discussed above it relies on the cube compressive strength test as the only standard test. It is well accepted that the cube compressive strength test is a bulk index test and offers no indication of the durability of the concrete cover layer. Also the cube test is not able to indicate compliance with specified site concreting practices of adequate compaction and curing.

While the European codes expand their durability specifications somewhat to include limits on crack widths, minimum air content, maximum aggregate size and water penetration they also ultimately rely on the cube or cylinder compressive strength test. A few codes make use of a water penetration test, however the tests have been severely criticized given their sensitivity to in-situ moisture conditions of the concrete.

2.8.2 INADEQUACIES OF CURRENT SPECIFICATIONS

It is generally felt among researchers that the current approach offers too little guidance on achieving durable concrete. Specifications are passive and imply durability rather than directly specifying it. Clearly standard tests, which measure the durability-related properties of concrete to assess compliance with a specification are lacking. Only when this is in place will it be possible to assess compliance or non-compliance with a set durability standard.

A complete concrete specification would need to provide a balanced set of concrete characteristics and the means to measure them which takes into account all requirements for construction, structural capacity and durability i.e. cover to steel, permeation properties and chemical resistance.

To specify durability performance characteristics, there are three requirements:
- A suitable durability measure for specification and compliance purposes;
- A simple and reliable test; and
- A test method that is suitable for site use.

The links between permeation properties and durability have long been recognized and it has been suggested that permeation tests point to a way forward in specifying concrete by performance related criteria.

2.9 THE INDEX APPROACH TO ACHIEVING DURABLE CONCRETE

2.9.1 DURABILITY INDEX TESTS AS A POSSIBLE SOLUTION

Over the past few years a number of tests have been developed which measure the transport of fluids and gases through the cover layer of concrete. The tests simulate transport mechanisms that facilitate the deterioration of the concrete and the results have been found to be sensitive to variations in concrete quality and durability which can arise from differences in materials, water/binder ratio, binder content and type, compaction, curing, environment etc. Results from these tests on early age concrete have also to a certain extent been correlated with the long-term durability performance of concrete structures. The test results are however, not absolute measures of the material properties of the cover concrete, but are "index" values, and can thus be used for comparative and control purposes.

The test results have been found to be reliable and able to give single parameter assessments of the effectiveness of various mix design parameters and curing procedures in developing the pore structure of the cover concrete. This is achieved by measuring specific material properties of the concrete such as water absorption, chloride diffusion and permeability. Therefore the potential exists that early age results of these tests on concrete could possibly be utilized as follows:

- To control the relevant durability properties of the cover layer of concrete during construction by specifying limits for the index values at 28 days;
- As a means of assessing the effectiveness of site practices and the quality of construction for compliance with the specifications;
- As a basis for fair payment for the achievement of concrete quality on-site; and
- To predict the long-term durability performance, i.e. the service life, of concrete in its design environment.

2.9.2 AVAILABLE TEST METHODS

A wide range of durability tests are described in literature and Table 2 gives a summary of the most well-known of these tests as well as their relation to the different transport properties and the method of testing. Where the particular test has been taken up in a specification, it is also shown.

2.9.3 DURABILITY INDEX TESTS AS A MEANS OF CONTROLLING DURABILITY-RELATED SITE PRACTICES AND DESIGN CRITERIA

Table 3 shows the durability related factors for which the various tests have been found to be sensitive.

TABLE 2: AVAILABLE CONCRETE DURABILITY TESTS *(Adapted from Bouwer[6])*

IN SITU/ LAB BASED:	IN SITU TESTS	LABORATORY BASED TESTS			
TRANSPORT PROPERTY:	ABSORPTION	ABSORPTION		PERMEABILITY	IONIC DIFFUSION
METHOD OF TESTING:	Measurement of Penetration depth	Shallow Immersion, Measurement of Mass increase	Measure depth of penetration by sample splitting	Pressure induced flow	Measure the Conductivity
	Initial surface Absorption test (ISAT)-BS 1881 part 5	Kelham's water Absorption test	ISAT by Ho et al,	Water Penetration test – DIN 1048 in EN206	Streicher's Chloride conductivity test
	Figg's method of ISAT	Ballim's water Sorptivity test	Figg by Ho et al	Clam test	Rapid chloride Permeability test - AASHTO T277 and ASTM 1202- 91
	Covercrete Absorption test	Absorption test BS 1881 Part 122	CAT by Ho et al	Autoclam test	Dundee accelerated Chloride diffusion test
		Absorption test - ASTM C497		Hansen's gas Permeability test	
		Absorption test - AS 1342		Figg air and water Permeability test	
		Rate of capillary Absorption test		Ballim's oxygen Permeability test	

Since the durability index tests are related to design criteria such as cement type and water/cement ratio, concrete mixes could now be designed with a potential durability index as objective. Whether or not this potential durability is achieved, will then depend on-site practices such as curing and adequacy of compaction.

2.9.4 RELATING DURABILITY INDEX TESTS TO THE TRANSPORT PROPERTIES OF CONCRETE

The results of some of the durability tests that have been developed have been specifically related to the transport properties of concrete. These are the following:

- The Initial Surface Absorption Test (ISAT) determines the rate of water absorption into concrete, and the Figg test measures the air permeability of concrete.
- In Kelham's sorptivity test the square root of the measured sorptivity is directly related to the intrinsic permeability as well as the capillary forces, and inversely related to the effective porosity of the concrete. This same relationship is used in the simplified version of the test that was developed by Ballim, in South Africa.
- In Streicher's chloride conductivity test the measured conductivity is related to the diffusibility ratio and thus the chloride diffusion of the concrete.

TABLE 3: DURABILITY INDEX TESTS AND THEIR RELATED FACTORS (PER LITERATURE) *(Adapted from Bouwer[6])*

TEST	DURABILITY RELATED FACTORS					
	SITE PRACTICES		DESIGN CRITERIA			
	Adequacy Of Compaction	Curing	Cement Type	Water/ Binder Ratio	Aggregate Size	Concrete Grade
ISAT		x	x	x	x	x
Ballim's oxygen Permeability test	x	x	x	x		x
Ballim's water sorptivity Test		x	x	x		x
Streicher's chloride Conductivity test		x	x	x		
Autoclam test		x	x			
Figg's version of ISAT				x		
Absorption test ASTM C642		x	x			
Water permeability test DIN 1048		x	x			
Chloride permeability Test AASHTO T277		x	x			
Kelham's water Absorption test		x	x			
CAT		x		x		

2.9.5 PREDICTING THE SERVICE PERFORMANCE OF CONCRETE

Since one of the main aims of the durability index approach is to predict the long-term durability performance, i.e. the service life, of concrete in its design environment, researchers have also started to try to relate the durability indexes to some of the long-term characteristics of concrete, in particular deterioration mechanisms. Although the data is still sparse, there are indications of the usefulness of the tests in this respect.

Relationships have been shown to exist between the ISAT test and different deterioration mechanisms such as freeze-thaw effects, carbonation depth, and chloride diffusion and abrasion depth. The South African water sorptivity test results of laboratory concrete have also shown good correlation with carbonation. A lot more research will still have to be done in this respect before the durability index tests can be put to proper use.

2.9.6 PROBLEMS STILL FACING THE INDEX APPROACH

A lot of research work has been undertaken on the durability index testing of concrete, however there remain many problems to be resolved prior to the acceptance of the approach as an accepted standard. According to European researchers this approach was not included in the latest European Standard for Concrete, the EN206, since it was believed more work is required to clarify some issues, particularly acceptance limits. Researchers in the field have also indicated that most of the information from tests on durability related aspect of concrete is fragmented and a lot of work is required to synthesize the data.

2.10 IMPLEMENTATION OF DURABILITY INDEX TESTS IN SOUTH AFRICAN PRACTICE

2.10.1 A NEW PROPOSED SPECIFICATION

South African researchers in the field of concrete durability have indicated that current practice in ensuring the production of durable structures is too haphazard to guarantee the achievement of design life of concrete structures. They further point out that the existing cube compressive strength is insufficiently sensitive to establish if the in-situ concrete has been properly constituted, placed, compacted and cured. They thus stress the need for an in-situ test to measure durability related material properties of the concrete as well as implementing these tests into contract specifications.

2.10.2 DURABILITY INDEX TESTS FOR SOUTH AFRICA

It is well accepted by South African researchers that due to the complex nature of concrete deterioration, no single durability test will satisfactorily measure the potential durability of all concrete applications. Therefore defining the durability of concrete by measuring only one material property may be misleading if that property is not sensitive to other forms of deterioration which might take place.

For this reason, three durability index tests have developed and refined by South African researchers during the past five to ten years for the purpose of implementation in practice for the assessment and control of concrete durability, as follows:

- Ballim water sorptivity test;
- Ballim oxygen permeability test; and

- Streicher chloride conductivity test.

The three tests have been chosen for implementation in practice, since each is a measure of a different transport property of the cover layer of the concrete, namely the permeability of the concrete, the absorptivity and the rate of ionic diffusion of the concrete.

2.10.2.1 The Water Sorptivity Test

The water sorptivity test measures the rate at which water is absorbed into a concrete sample through absorption. The lower the water sorptivity index, the better is the potential durability of the concrete.

It has been shown that absorption rates of concrete reduced with increasing grade of concrete and the extent of active moist curing. Wet curing and moist curing produced similar results while dry cured concrete exhibit significantly higher sorptivity values. The sorptivity test essentially measures a surface phenomenon and should therefore be sensitive to early age drying effects, which affect the microstructural porosity gradient in the concrete, making the test useful in assessing curing efficiency.

Table 4 shows the suggested range for durability classification using the index values, developed in a decade of research in South Africa.

TABLE 4: SUGGESTED RANGES FOR DURABILITY CLASSIFICATION USING INDEX VALUES.

DURABILITY CLASS	OXYGEN PERMEABILITY INDEX	WATER SORPTIVITY INDEX (mm/√hr)	CHLORIDE CONDUCTIVITY INDEX (mS/cm)
EXCELLENT	> 10	< 6	< 0,75
GOOD	9,5 – 10	6 – 10	0,75 – 1,50
POOR	9,0 – 9,5	10 – 15	1,50 – 2,50
VERY POOR	< 9,0	> 15	> 2,50

It was found that OPC concretes have higher sorptivity values than either FA or GGBS concretes when moist or wet-cured, showing the advantages that cement extenders can give when correctly treated. Dry cured concretes showed the opposite trend with FA and GGBS concretes having higher sorptivities than OPC concrete. The benefits of using cement extenders can therefore be lost if poorly treated on-site.

2.10.2.2 The Oxygen Permeability Test

The oxygen permeability test involves a falling head permeameter that measures the oxygen permeability index of concrete. The coefficient of permeability is determined from the slope of the line produced when the log of the ratio of initial pressure to decaying pressure is plotted against time.

The test measures the gas permeability of the concrete and the oxygen permeability indexes are on a log scale and range from 8 to 11, i.e. three orders of magnitude. Furthermore, the higher the index, the less permeable is the concrete.

Recent research indicated that the oxygen permeability indexes increased, the permeability therefore reducing, with increasing grade of concrete and extent of active moist curing. FA and GGBS concretes were shown to be less permeable than OPC concretes when well cured but were more permeable than OPC concrete when dry cured. Oxygen permeability indexes are shown to be more dependent on the amount and continuity of larger pores in the concrete where most of the flow will occur and which is likely to have been caused by poor compaction or bleeding. The test is further shown to be less sensitive to the finer capillaries and did not reflect the inherently fines pore structure which is characteristic to FA and GGBS concretes. Another study showed that the oxygen pemeabilities of lower strength concretes were much more sensitive to the duration of wet-curing than higher strength concretes.

2.10.2.3 The Chloride Conductivity Test

Chloride diffusion through concrete is the main process by which chlorides enter into concrete in the marine environment. Fairly recently a rapid chloride conductivity test has been developed at the University of Cape Town in which virtually all ionic flux occurs by the process of conductivity due to a 10 V potential difference.

In the chloride conductivity test, chloride ions move through all pores of sufficient size, without favoring the larger pores as with the permeation process. The movement is due to the existence of an electrical potential difference between the two faces of the sample. The chloride conduction test therefore provides a good indication of the overall diffusivity of the material, the test being sensitive to changes in the pore structure and concrete chemistry, which might appear to be insignificant when using the permeation process. Furthermore chloride conductivity was found to be extremely sensitive to pore structure changes caused by varying amounts of curing and by using different types of concrete. The lower the index, the lower is the diffusibility of the concrete and the better the potential durability of the concrete.

A study showed that 28-day chloride conductivity indexes reduced with increasing concrete grade, but were more affected by the extent of curing and the type of cement. When properly cured, the addition of FA or GGBS has the effect of refining the pore structure chemistry of the concrete and the chloride conductivity test has been found to be extremely sensitive to such changes.

2.10.3 The Implementation of the Durability Index Tests in Practice

The intended purposes of the three tests on construction sites in South Africa are the following:

- to be used as a construction specification in which limits to the index values at 28 days are specified in order to control the quality of the surface layer of the concrete;
- to assess the quality of construction;
- as a basis of payment; and
- as a means of predicting the performance of the concrete in the design environment.

The chosen tests have been developed and proved in the laboratory, but have not been performed on actual structures to any great degree. The three tests need to be evaluated for practical applications on actual structures. This evaluation process would establish the following:

- the influence of construction methods, design parameters and environment on the index values;
- determine whether the index tests are in fact realistic and executable in practice;
- provide standardized parameters for sampling rate, compliance criteria and the method statements of the testing procedure;
- start generating a database from which to draw up performance based specifications for constructing durable concrete structures; and
- set up a systematic system of working and data generation to ensure the continuation of the project so that the index values could be used for predictive purposes.

2.11 CONCLUDING REMARKS TO SECTION 1

This author concludes that Bouwer's review of the literature was both accurate and articulate. She presented a detailed review of the available literature with a strong theoretical leaning. In the writer's opinion, one of the shortcomings of the review was that it did not present a background or history of the index approach in South Africa and did not clearly summarize the findings of a number of years of research in this field (in a South African context).

The writer's own review thus endeavors to expand these areas of the field and has a far more practical leaning, given the nature of the project.

SECTION 2: ADDITIONAL LITERATURE REVIEW PREPARED BY WRITER (2002)

2.12 INTRODUCTION

This additional review prepared by the writer begins by outlining the history of the Durability Index Approach in South Africa and an assessment of the current status of the project. Following this, new literature is discussed highlighting new information in addition to the summary prepared in Section 1.

2.13 HISTORY OF THE DURABILITY INDEX APPROACH IN SOUTH AFRICA

2.13.1 BACKGROUND

According to Ballim et al[7], the durability research programme in South Africa was launched in 1990 at the University of the Witwatersrand. Prior research activity in South Africa had been undertaken by the NBRI (National Building Research Institute), now the Division of Building Technology (DBT) of the CSIR (Council for Scientific and Industrial Research). Their research effort focused on developing an understanding of the durability of concrete in broad terms with the aim of increasing awareness in the industry.

The above developed into a general Research Programme in Concrete Materials with emphasis on issues of durability and deterioration of concrete. The programme was initially sponsored by the FRD (Foundation for Research Development), the cement industry and LTA Construction. The movement of Prof. Alexander from the University of the Witwatersrand to the University of Cape Town not only increased the base of students and facilities available to the programme, but also added a new thrust to the programme in terms of marine concrete degradation.

2.13.2 DEVELOPMENTS IN THE PROGRAMME OVER THE LAST DECADE

The most significant product of the programme was the development of three Durability Index Tests viz. Oxygen Permeability, Water Sorptivity and Chloride Conductivity tests. These tests measure the fluid transport properties of the covercrete with the aim of assessing the quality of the covercrete, which in turn indicates the ability of the concrete to resist the movement of fluids into the concrete.

The development of these tests allowed the assessment of the influence of a range of factors, reflecting the concrete mix and construction practice, on the potential durability of concrete. At the same time, efforts were directed at developing correlations between early age index results and long-term durability performance of concrete[7].

Currently at least five commercial organizations in South Africa own and operate the equipment necessary to determine the durability indexes of concrete. In addition to this owners of large concrete infrastructure have showed interest in the project as also a number of concrete practitioners. At least two large owners of concrete infrastructure have specified the use of durability index tests to ensure compliance with a minimum standard[7].

2.13.3 CURRENT STATUS OF PROGRAMME

The programme has moved to the level where the use of the Durability Index approach requires practical site-based work to determine not only the success of the test but also to make recommendations regarding practical implications in achieving durable concrete[7]. One of the ultimate aims of this programme is to provide a revised performance-based South African durability specification together with practical guidelines on how to achieve durable concrete in various environments[7]. This aim or shift in focus gave direct rise to the study described in more detail in section 2.18 below.

2.13.4 SOME THOUGHTS ON FUTURE STRATEGIC DIRECTIONS

There are six main areas of strategic direction, or thrusts, relating to this programme, according to Ballim et al[7].

1. ***Service Life Modeling and Prediction:***
Based on the test results and understanding developed, provide a comprehensive durability design model for South African conditions.

2. ***Minimum Standards for Durability:***
There exists a need to quantify the minimum acceptable standards to ensure durable concrete in South Africa.

3. ***Durability Monitoring:***
There exists also a need to develop equipment, procedures and facilities which will allow owners of concrete structures to monitor the rate of deterioration of their structures.

4. ***Repair and Rehabilitation:***
There is a need to better understand the procedures, materials and processes currently used in concrete repair.

5. ***Drafting of Specification to Achieve Durable Concrete Construction:***
The research data must be translated into practical specifications to ensure construction practices that culminate in durable structures.

6. ***Investigate New Concrete Materials in South African Context:***
The tools developed in this programme can be used to evaluate the new materials entering the concrete industry and their influence on durability of concrete.

2.14 CHARACTERIZING THE EFFECT OF THE ENVIRONMENT ON DURABILITY INDEX PROPERTIES OF CONCRETE

2.14.1 BACKGROUND

Hoff[8] indicated that the effect of the environment is pivotal in the durability of concrete, and that currently little or no information exists in relating to the rate of degradation of a concrete member subject to a particular environment. He further indicated that codes of practice offer little guidance in this respect and tend to group or generalize exposure environments. Slater and Sharp[9] reinforced these opinions and indicated that this lack of knowledge was a fundamental shortcoming, requiring urgent attention. While these comments relate to the broader exposure environment (marine or other), the same is true for environmental (climatic) influences. Little or no quantitative information is available on the degradation of concrete in various conditions of ambient temperature, precipitation and relative humidity. Based on the above observations the writer realized the need to develop a system where the effect of the various environmental influences (precipitation, temperature and relative humidity), experienced by the test elements, could be classified in order to compare them. This project was undertaken on-site over a period of four seasons and the test elements were subjected to variations in climatic environment.

In a recent study undertaken by Griesel[10], the effects of environmental conditions on the durability index values were quantified. His work was pivotal to this project, in that it facilitated the raw data to develop a broad environmental characterization system as set out in Chapter 4 of this dissertation. The section below highlights the key findings of Griesel's study.

2.14.2 TEMPERATURE

Griesel[10] used three grades of OPC (supplied by PPC) concrete (20, 40 and 60 MPa), wet-cured for 1, 3, 7 and 28 days, and exposed to variations in temperature and relative humidity. He found that temperature significantly influenced the potential durability of concrete as measured by the index tests. He proposed that the temperature effect was twofold, in that it influenced both the rate of hydration

of the cement, as well as the rate of evaporation. These two effects are constantly in competition and elevated temperatures could either improve or impair the potential durability of the concrete. The importance of proper curing was accentuated as discussed in 2.14.4 below.
Griesel[10] found that inadequately cured concretes (1 day of wet curing) lost their moisture rapidly at a temperature of 35°C and performed very poorly, while well-cured concretes appeared to benefit from the accelerated rates of hydration at this temperature.

2.14.3 RELATIVE HUMIDITY

Griesel[10] found that above 80% RH, the rate of evaporation slows down significantly and results in good durability as indicated by the data in Table 5. Once again the importance of proper curing was accentuated as discussed in 2.14.4 below.

Griesel indicated that well-cured concretes were insensitive to changes in relative humidity, while poorly cured concretes exhibited a marked improvement in durability properties with increase in relative humidity from 66% to 82%.

2.14.4 CURING OR PRECIPITATION

Tables 5 indicates the durability index results for 20 and 40 MPa concretes wet-cured for various lengths exposed to variation in temperature and a constant relative humidity (50% R.H).

TABLE 5: THE INFLUENCE OF RELATIVE HUMIDITY ON THE DURABILITY INDEXES OF 40 MPA CONCRETES (AT 19°C), WET-CURED FOR 1, 3, 7 AND 28 DAYS (FROM GRIESEL[10].)

		40 MPA		
	PERIOD OF WET CURING (DAYS)	**CL (mS/cm)**	**WS (mm/√h)**	**OPI (-log k)**
RH 54%	**1**	2,10	10,55	9,65
	3	1,93	9,60	9,91
	7	1,82	8,80	10,05
	28	1,77	8,70	10,07
RH 66%	**1**	2,07	10,55	9,67
	3	1,90	9,40	9,92
	7	1,81	8,80	10,06
	28	1,77	8,70	10,07
RH 82%	**1**	2,03	8,90	9,69
	3	1,88	8,80	9,93
	7	1,79	8,75	10,07
	28	1,77	8,70	10,07

From Table 5 the dramatic effect of curing is evident over the range of temperatures. Notice the substantial increase in durability properties when comparing 1 day and 3 days of wet curing. One of Griesel's conclusions was that the first 3 days after casting are crucial in terms of curing, to develop durable concrete.

TABLE 6: THE INFLUENCE OF TEMPERATURE ON THE DURABILITY INDEXES OF 20 AND 40 MPA CONCRETES (AT RH OF 50%), WET-CURED FOR 1, 3, 7 AND 28 DAYS (FROM GRIESEL[10].)

		20 MPa			40 MPa		
	PERIOD OF WET CURING (DAYS)	**CL (mS/cm)**	**WS (mm/√h)**	**OPI (-log k)**	**CL (mS/cm)**	**WS (mm/√h)**	**OPI (-log k)**
T=19°C	1	3,5	15,6	8,9	2,10	10,40	9,60
	3	3,0	12,9	9,2	1,90	9,80	9,90
	7	2,8	11,6	9,4	1,80	8,80	10,10
	28	2,6	10,8	9,4	1,77	8,70	10,07
T=28°C	1	3,2	16,0	9,0	2,20	10,40	9,90
	3	2,8	12,0	9,2	2,00	9,20	10,10
	7	2,6	10,9	9,5	1,80	8,70	10,20
	28	2,6	10,8	9,4	1,77	8,70	10,07
T=35°C	1	4,3	22,2	8,5	2,20	13,20	9,40
	3	3,0	14,4	9,3	1,81	9,80	9,50
	7	2,5	12,2	9,5	1,62	8,70	9,60
	28	2,6	10,8	9,4	1,77	8,70	10,07

Without the data developed by Griesel it would have been impossible to develop the broad characterization system as set out in chapter 4 of this dissertation. Up to that stage no model existed which showed the relationship between the environmental factors and the durability indexes. This also highlights the benefit of a centralized research programme currently undertaken by the University of Cape Town and the University of the Witwatersrand.

2.15 WHY DURABLE CONCRETE IS NOT BEING ACHIEVED ON A GLOBAL SCALE

2.15.1 COVER

A discussion document published by the Concrete Society in 1996[11] ascribes failure to achieve the specified cover as the greatest single factor influencing the premature corrosion of reinforcement. It further indicated that broadly the protective capacity of any given concrete is proportional to the square of the cover.

This document[11] also goes to great lengths to explain that current practice regarding specification of a single minimum cover is not practical, and measured cover after casting reveals a Gaussian distribution about the specified minimum cover. Sharp[12] also raised this issue indicating that to specify a minimum cover lulls designers into a false sense of security, for the same reason as above. Both of the above references[11,12] propose the following amendments to the cover specification:

- *Nominal cover* - assumed as mean cover, specified on drawings, size of cover blocks.

- *Characteristic minimum cover* - cover represented by the 5th percentile of population, used for durability design.
- *Characteristic maximum cover* - cover represented by the 95th percentile of population.
- *Lowest cover* - value below which no individual values are to fall.

Harrison[13] reports that a substantial research project conducted by the University of Birmingham measured cover achieved on 25 construction sites and identified the causes of non-conformance with cover as follows:

- Unbuildable designs and detailing.
- Poor workmanship.
- Poor communication and co-ordination.

In a paper[14] describing the design and construction of concrete elements of the "New South Railway" Project in Sydney, Australia, in order to achieve a design life of 100 years, it is noted that the specification and control of adequate cover to all surfaces was one of the key "limits" or "tools" used to reach the objective. A similar trend is noted for the construction of the concrete infrastructure for the "Öresund Link", connecting Denmark to Sweden[15]. Covers of 75 mm were specified on the external surfaces of the bridge structure with a design life of 100 years.

2.15.2 CURING

In an extensive appraisal of curing in the UK[16] undertaken by CIRIA in 1973, it was established that a wide range of opinions exists regarding the practicability of curing and there is large disparity between curing specifications and the way they are interpreted. The authors also indicate that apart from shrinkage cracking in pavements, all of the surveyed completed concrete works in the UK exhibited no visible defects directly related to curing method or lack of curing. The writer's own opinion is, however, that this statement must be viewed within the context of the relatively benign environment experienced in the UK and not be extrapolated to conclude that curing has no visible benefit in all environments.

The study[16] further indicates that the popularity of spray-applied membranes prompted the initiation of a limited test to determine the moisture retention properties, the results of which revealed extensive variation in the efficiency of the curing method. The study did concede that there exists a fundamental lack of knowledge in terms of the ultimate long-term effects of curing and that future research needs to evaluate the long-term value of curing in-situ with respect to durability.

In a more recent study by the same institution[17] in the UK, an extensive review on available literature was prepared, and suggested research to evaluate the effectiveness of various curing methods on the production of durable concrete structure as follows:

- Evaluation of measured values of surface properties required in full scale structures to indicate that concrete with adequate durability has been achieved for given cementitious material mix proportions, early age conditions and type of exposure.

- Detailed evaluation of the test identified above as a potential practical method of assessing the effectiveness of curing on a range of performance criteria.
- Economic evaluation to determine the most cost-effective method of producing durable concrete.

The publication[17] went further to indicate a range of performance criteria to be investigated in relation to issues as listed in Table 7 below.

TABLE 7: PERFORMANCE CRITERIA TO BE INVESTIGATED, AND SPECIFIC ISSUES REQUIRING ATTENTION *(From CIRIA Report 49[17].)*

DURABILITY CRITERIA	**RESEARCH ISSUES**
Freeze Thaw Resistance	Effect of curing unclear from published research and further work is required to establish the influence of practical on-site curing on this property.
Carbonation	Curing shown to be beneficial, however optimal regime needs to be identified and the influence of the environment conditions evaluated.
Chloride Penetration	A critical performance criterion for which the effect of curing is unclear from published research. Priority research programme required determining the influence of different curing regimes on a range of concrete mixes, under different environmental conditions.
Alkali-Silica Reaction	No published research on the effect of on-site-curing. From a theoretical standpoint the effect is likely to be small thus appears to be a low priority item for future research.
Sulphate resistance	Air exposure at early age is known to be beneficial. Further research work is required to confirm the optimum regime for the treatment of concrete expose to sulphate attack, particularly in relation to other durability properties.
Abrasion resistance	Curing known to be beneficial. Optimal regime needs to be identified and the benefits of curing assessed in relation to the influence of other factors such as surface finish.
Plastic shrinkage	Curing known to be beneficial. Optimum or minimum to prevent plastic shrinkage cracking needs to be confirmed.
Structural performance	Curing is unlikely to have a significant effect for a majority of components and further research only required in relation to the its influence on the structural performance of thin highly stressed members.

It is clear from the above publications that the influence of site-curing on concrete durability is not well established, notwithstanding the beneficial effect of wet curing as indicated by Griesel[10] and Mackechnie [18]. This is one of the primary focuses of this study and it is hoped that clear guidance will emerge on the effectiveness of various site-curing methods, in achieving durable concrete.

2.15.3 CURRENT CODES OF PRACTICE

As highlighted in the previous section of this chapter the South African concrete code presents real deficiencies in terms of a durability specification for concrete. Collins and Grace[19] indicate in a recent publication that the Australian concrete code exhibits shortcomings in that it does not require the designer to specify a design life for a structure. They[19] indicate that BS 7543 "Durability of buildings, building elements and components" and also "Principal guide for service life planning of buildings" released by the Architectural Institute of Japan have moved towards clear definition of the design life. Cao et al [20] indicate that the code offers no suggestions should a design life exceeding 40-60 years be required. They further indicate that by using Fick's second law of diffusion calibrated with locally generated data, concretes subject to marine exposure conditions designed to the current Australian concrete code will not meet the 40-60 year design service life, unless a suitable binder is selected.

Other researchers[21] also point out that the code offers no indication of the derivation of the thickness and class of covercrete, with respect to design life. The same researchers also indicate that the lack of long-term chloride penetration data makes design for an extended service life in marine environments somewhat difficult[21].

Collins and Grace[19], in a paper on design and construction of oil drilling platforms in the Bass Strait in the Tasmanian Sea, explain how the designers developed a computer model calibrated on a reinforced concrete structure in Hong Kong, to predict chloride ingress into the concrete and thus develop concrete able to meet a 30 year design life. Interestingly a quaternary blend of 50% portland cement, 35% GGBS, 10% FA and 5% CSF was used for the construction of the structures.

Hoff [8] supports the view taken by Collins and Grace[19] that a performance life requirement should be set out for every structure, regardless of uncertainties etc. He further indicates that firmer guidance on defining the environment in which the concrete is used is necessary and will require substantial expansion of the current standards, which are very generalized and consider only simple environment scenarios.

Hoff [8] further proposes that the performance criteria of concrete must focus on the transport properties of the concrete, and in the current "vacuum", code writers should adopt the following approach:

- minimum binder content of 400kg/m^3
- maximum water/binder ratios of 0,38
- prohibitions on the use of GGBS, FA and CSF are not acceptable

2.15.4 OTHER

Hoff[8] further indicated that there exists a perception among clients and owners that the initial capital cost of this "high performance" concrete is unjustified. He goes on to add that this perception can easily be overcome by lifecycle costing, comparing the initial capital outlay with the subsequent repair cost. He draws an analogy to a long running television commercial in the U.S. promoting the sale of automobile oil filters, concluded by having the auto repair mechanic saying, "You can pay me now or you can pay me later!" The inference was that if you paid a little more for the oil filter you used in your automobile, you wouldn't have to pay for costly repairs in the future. The same is true for concrete.

In a recently published paper Harrison[22] is of the opinion that in most cases the premature degradation of concrete could have been prevented by the application of existing knowledge. He bases this premise on his experience that poor design, detailing, workmanship and lack of communication cause premature degradation of concrete. Hoff [8] quotes Bryant Mather, world-renowned expert on concrete durability, as often stating that the only reasons concrete should deteriorate are ignorance, stupidity or fraud. While there exists no illusion about the prevalence of poor practice relating to design, detailing and workmanship, the current codes of practice are clearly deficient in assisting with respect to designing durable structures.

2.16 PERFORMANCE SPECIFICATIONS AS A MEANS OF ACHIEVING DURABLE CONCRETE

2.16.1 PROGRESS

Sharp[12] indicated in a paper published in 1996, that a great deal of work is required before coastal structures can be specified by performance. At about the same time Harrison[23] indicated that tentative performance criteria for concrete to resist carbonation induced corrosion were proposed by CEN but had not yet proven to be suitable for specification purposes. More recently, Slater[9] indicated that a large amount of work is currently underway on developing strategies for a durability specification for structures exposed to chlorides, particularly marine structures.

2.16.2 PROBLEMS

In a recent detailed investigation[24] into the use of the permeability of concrete as a criterion to assess its durability, it was shown that the results depend on the preconditioning, and hence the need for a standard procedure for preconditioning. It was also shown that results are very sensitive to test procedure (particularly the water content of the specimen). Dhir et al[25] indicate that existing preconditioning techniques for permeation testing are unsuitable for in-situ compliance testing.
Sharp[12] indicated that, given the current situation regarding the availability of information on performance criteria and required service life of concrete structures, more information is required before owners and operators can use performance criteria to specify a minimum design service life.

Kropp[26] et al indicate that the current durability specifications are empirically based i.e. designers draw on experience with materials used under known exposure conditions. This approach not only counteracts technological progress but can at times be misleading.

Harrison[13] commented that a water penetration test was shown to exhibit a high degree of variability and provided no direct correlation with quality of concrete, with a the result that both the European Concrete Standard and British Standards Institute have agreed to remove this test from their specification. He also reports in a prior publication[23] that exposure classes that are suitable as a basis for performance specification have been developed by CEN, however further refinement may be necessary.

2.16.3 CORRELATION

Kropp[26] et al indicate that the perviousness of a concrete section can be expressed by transport coefficients for various media. However it is necessary to distinguish between different transport mechanisms such as diffusion, permeation and capillary suction and also different media such as ions, liquids or gasses. Depending on the type of corrosive agent, the relevant transport mechanisms include:

- the diffusion of gas molecules such as O_2 or CO_2 or water vapour in the gaseous phase.
- the diffusion of ions into the concrete pore solution.
- the permeation of water or aqueous solutions under influence of a hydraulic pressure head.
- the capillary suction of water or aqueous solutions.

Studies have revealed[26] that close correlation was shown to exist between the gas permeability of concrete and:

- the rate of carbonation
- depth of chloride penetration

In a similar manner close correlation was shown to exist between the capillary suction of concrete and:

- carbonation rate
- chloride ion ingress

These authors[26] note, however, that extender materials interact with the chemical attack mechanisms and their behaviour cannot be explained by transport properties alone.

Dhir et al[25] indicated that concrete durability can be classified in terms of initial surface absorption but allowance must be made for binder type when the aspect of durability considered is other than purely physical. Harrison[23] commented that freeze/thaw tests have the potential to form the basis for performance testing.

2.16.4 PROPOSED TESTS

In a recent detailed investigation[24] into the use of the permeability of concrete as a criterion to assess its durability the results supported the Cembureau gas permeability method and modified Fagerlund method for testing capillary absorption of water as routine test methods. Dhir et al[25] proposed the ISAT-10 to be the most suitable test for reasons of economy, repeatability and definition of test methodology in the British Standards. Harrison[23] indicated that performance requirements for the chloride exposure are less developed.

Sirivivatnanon et al[21] indicate that the lack of long-term chloride penetration data in the Australian concrete code, makes design for extended service life difficult. However using Fick's second law together with a one-year laboratory determined chloride penetration profiles as calibration, they were able to develop a chloride penetration model for three various binders over a range of compression strengths. By relating the penetration profile of the tested concretes to compressive strength, they were able to achieve a good correlation and use the bulk property test as a durability quality indicator. They found that the binder type had a significant influence on the required cover to reach a set design life. This indicates the lack of a rapid, easy test to measure chloride penetration in the Australian context.

2.16.5 THE WAY AHEAD

Sharp[12] proposes that in the current "vacuum", the most obvious, easy positive step is to increase the specified cover and take cognizance of the idea that cover follows a normal Gaussian distribution and specify accordingly. Kropp[26] et al realize that there exists an urgent need to harmonise the various researches undertaken, and the various test methods and that further research work should focus on the effect of:

- critical evaluation of the various test methods
- concrete grades
- various binder types
- various attack mechanisms

Harrison[13] reports that CEN have approached RILEM to develop suitable test methods for chloride penetration and a report is awaited in this regard.
He[27] also proposes that the use of durability performance tests will evolve from research, through technical approvals, to the basis by which directly specified performance requirements are assessed. He further indicates that the industry is only likely to support standardisation of durability performance requirements if all the stages of evolution have been successfully completed. Hoff[8] agrees with Harrison[13] in this respect and points out that the process of integrating durability design into the structural design process will meet least resistance if the requirements are initially included in the national codes. Slater et al[9] indicates that the current durability specifications need to be critically assessed in the light of prevalent exposure conditions and that the key to assessing performance lies in data from real structures.

2.17 A DECADE OF DURABILITY INDEX TESTING IN SOUTH AFRICA

2.17.1 INTRODUCTION

Mackechnie[18] recently presented a summary of a decade of durability index test results (oxygen permeability, water sorptivity and chloride conductivity) highlighting some clear trends. While he indicated that simple analysis of the data was not possible given the number of variables a graphical representation of the data indicated some clear trends. The concretes tested during this period included material from all the major urban centres in South Africa but with particular emphasis on Gauteng and Cape Town.

2.17.2 EFFECT OF WATER/BINDER RATIO AND CURING

Mackechnie[18] re-iterates that the index tests were intended to be sensitive to material, processing and environmental factors affecting concrete. Two of the most important factors are water/binder ratio and initial curing of concrete.
Figure 1 shows typical oxygen permeability index results recorded at 28 days for portland cement concrete for both wet and dry curing. "Wet" refers to continuous wet curing of concrete for 28 days while "dry" refers to no active moist curing and laboratory exposure until testing (generally 23 ^{0}C and 60% R.H.).

Mackechnie [18] also noted a pronounced sensitivity to curing and water/binder ratio for oxygen permeability index results for FA and GGBS concretes as indicated in Figure 3 below. This is ascribed to the sensitivity of these materials to poor curing due to their slower strength development. This trend is repeated for water sorptivity results, as shown in Figure 2.

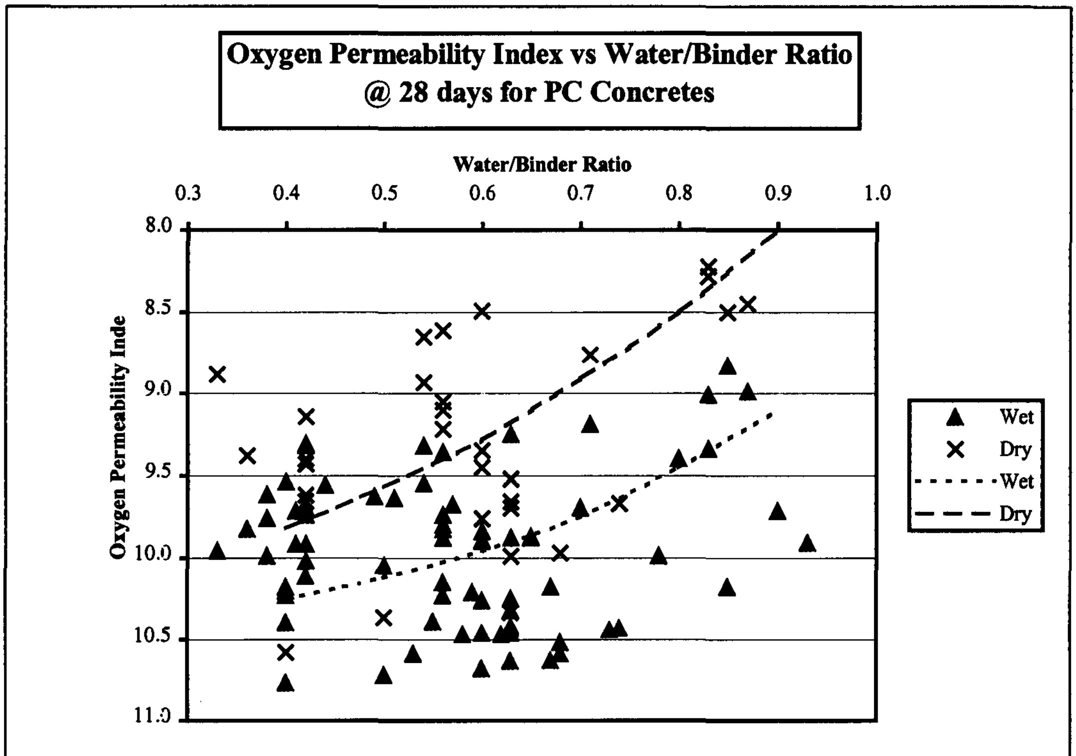


FIGURE 1: OXYGEN PERMEABILITY INDEX RESULTS AT 28 DAYS FOR PC CONCRETES (*Adapted from Mackechnie[18]*).

2.17.3 EFFECT OF BINDER TYPE

It was further pointed out by Mackechnie[18] that one of the primary aims of local research was to characterise the performance of new binder systems for concrete. The most common binder combinations used in South Africa are denoted PC (100% Portland cement), FA (30% fly ash), GGBS (50% slag) and CSF (10% condensed silica fume). Figure 3 clearly indicates that GGBS concretes consistently produce poorer oxygen permeability results, while FA and CSF concretes perform well.

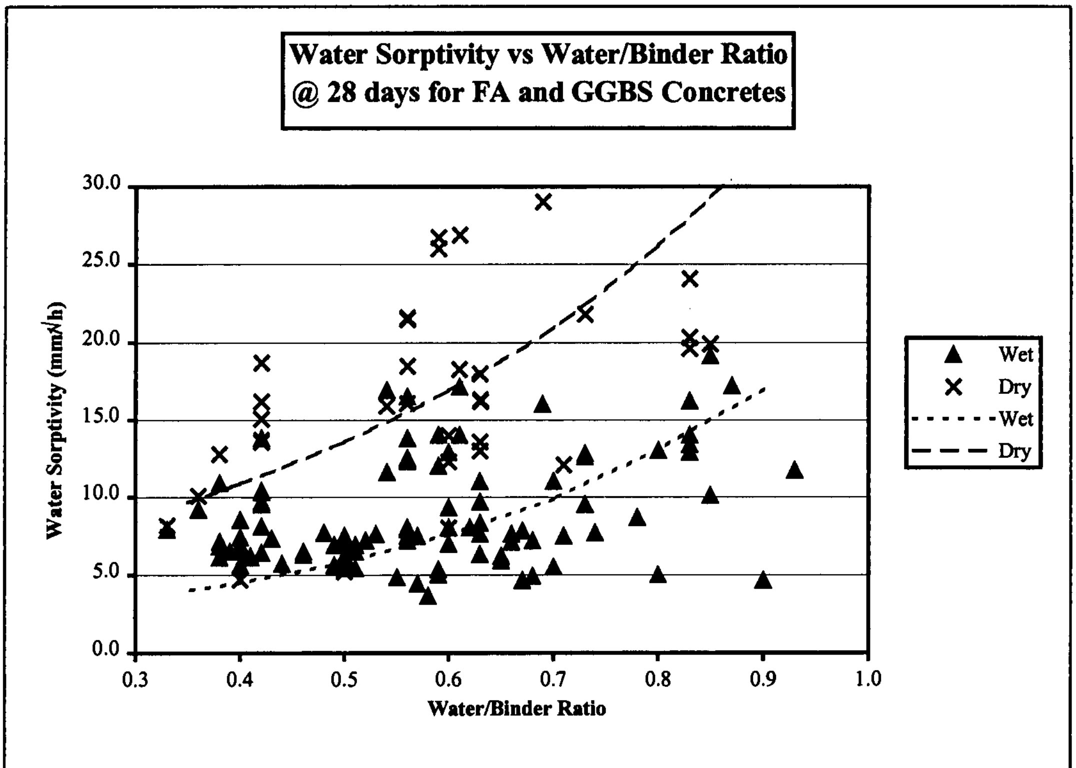


FIGURE 2: WATER SORPTIVITY RESULTS AT 28 DAYS FOR FA AND GGBS CONCRETES (*Adapted from Mackechnie*[18]).

Figure 3 shows general trend lines of oxygen permeability index test results for wet-cured concrete at 28 days.

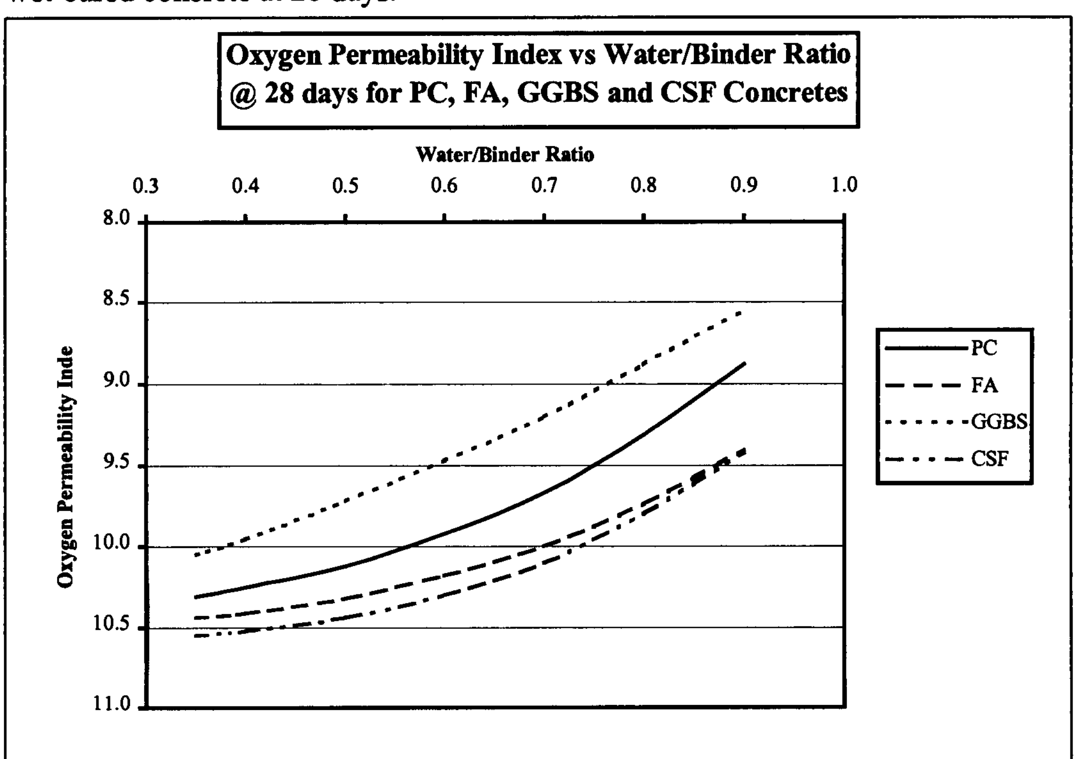


FIGURE 3: OXYGEN PERMEABILITY RESULTS AT 28 DAYS FOR WET-CURED PC, FA, GGBS AND CSF CONCRETES (*Adapted from Mackechnie*[18]).

Mackechnie[18] further indicates that the chloride conductivity test was found to be sensitive to the binder type used. PC concrete exhibited consistently higher values across all water/binder ratios whereas GGBS concrete had significantly lower chloride conductivity, particularly when well cured. Figure 4 shows chloride conductivity results for PC and GGBS concrete measured at 28 days after wet curing.

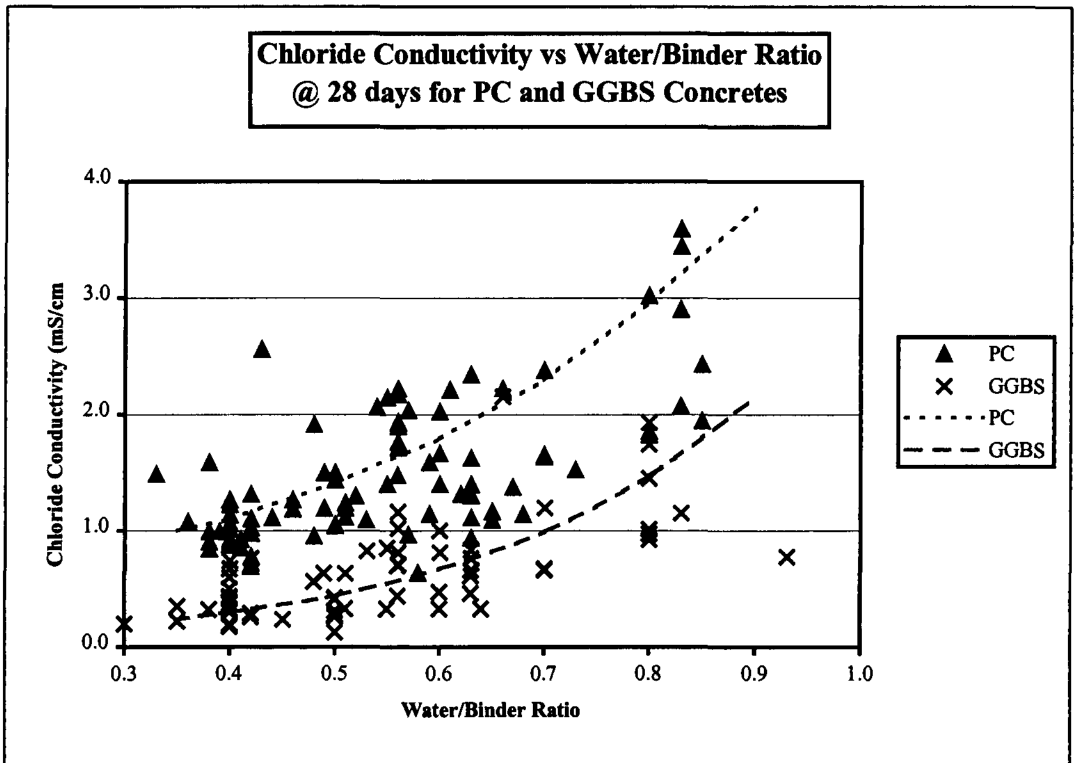


FIGURE 4: CHLORIDE CONDUCTIVITY AT 28 DAYS FOR WET-CURED PC AND GGBS CONCRETES (*Adapted from Mackechnie[18]*).

2.17.4 EFFECT OF AGGREGATE COMBINATIONS

Mackechnie[18] also showed that the durability indexes exhibited sensitivity to types of fine and course aggregate combinations used in the production of concrete. Figures 5 to 7 indicate this trend clearly. "Good" refers to combinations of high quality aggregates (e.g. dolerite/andesite crushed stone with dolomitic sands) while "poor" refers to low quality aggregates (e.g. crushed greywacke with poorly graded dune or pit sands).

2.17.5 OTHER EFFECTS

Mackechnie[18] also showed that the durability indexes exhibited sensitivity to operator precision. This was highlighted by variations in results obtained from two studies undertaken in the same laboratories over two varied time periods, using essentially the same concrete materials and conditions. Given that the tests are now better specified and the procedure is more streamlined, he[18] indicates that some of the discrepancies should now have reduced. Clearly a definitive study is required to assess the multi-laboratory precision of the tests. Mackechnie[18] also reports that this has not been undertaken to date (2001), although such an exercise is currently in place (2002).

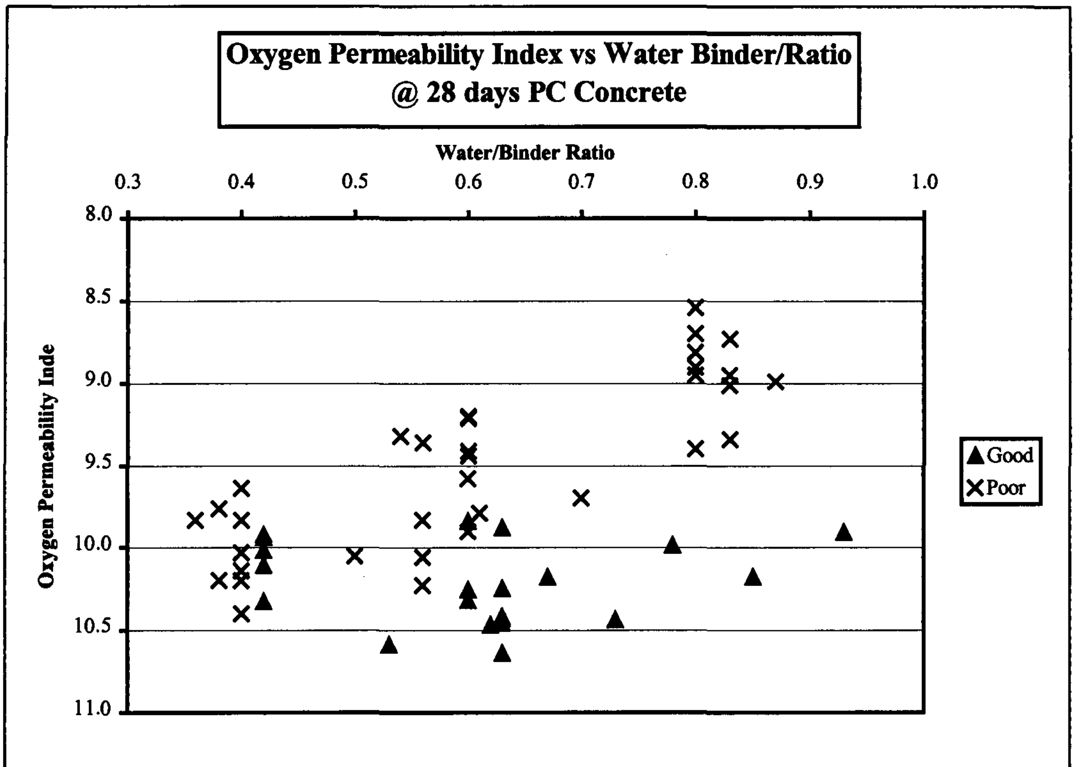


FIGURE 5: OXYGEN PERMEABILITY INDEX RESULTS AT 28 DAYS FOR WET-CURED PC CONCRETES, SHOWING INFLUENCE OF DIFFERENT AGGREGATES (*Adapted from Mackechnie*[18]).

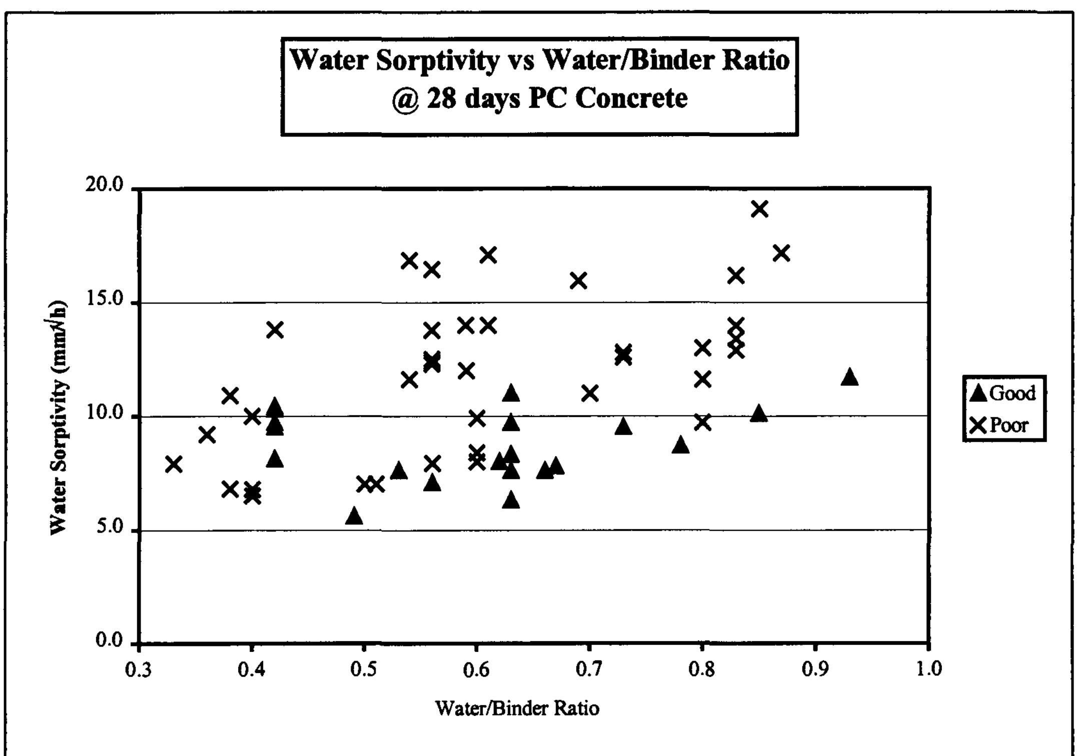


FIGURE 6: WATER SORPTIVITY RESULTS AT 28 DAYS FOR WET-CURED PC CONCRETES, SHOWING INFLUENCE OF DIFFERENT AGGREGATES (*Adapted from Mackechnie*[18]).

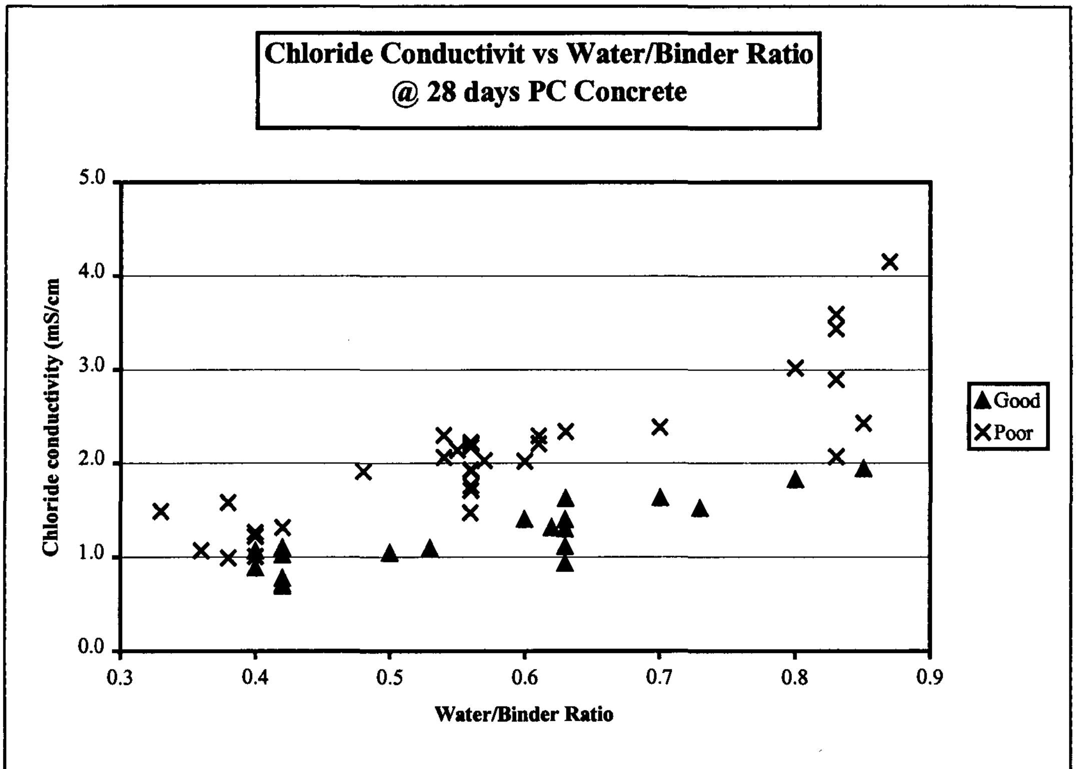


Figure 7: Chloride conductivity results at 28 days for wet-cured PC Concrete, showing influence of different aggregates *(Adapted from Mackechnie[18]).*

2.17.6 Conclusions

Mackechnie[18] concluded that the research showed that the durability indexes exhibited sensitivity to various factors which affect concrete quality and thus durability. The oxygen permeability index and water sorptivity tests are well suited to evaluating site practices, whereas the chloride conductivity test is more suitable for material optimisation.

It was thus suggested that the chloride conductivity test should be reserved for laboratory trials to determine optimal material combinations to ensure concretes resistant to chloride ingress. Mackechnie[18] further concluded that achieving durability index values as set out by some performance specification is possible using good material selection, optimisation and ensuring good construction practice. The converse is also true in that poor or indifferent materials selection, optimisation and site practices can yield extremely poor durability index values.

Bouwer[6] made similar observations in her study with the following statement, "In general, poor correlation was found between the indexes of the wet-cured cubes and of actual structures, revealing that even with good combinations of high quality mix constituents, poor quality can result on-site due to indifferent construction practices. Nevertheless, with due care, site indexes can equal or even surpass those of cubes cast under controlled conditions".

2.18 THE CONTEXT OF THIS PROJECT

2.18.1 AIMS OF PROJECT

The aims of this project are to produce, cure and manufacture concretes, from locally available materials, under site conditions, and examine their durability performance. In the material selection process, then current (1997) South African research findings (from the research programme as discussed in 2.13 above) were applied. While considerable care and attention has been taken to ensuring good construction practice, at the same time the project endeavors to remain relevant to current practice on construction sites in South Africa. In other words care has been taken to ensure that the study is representative of current South African site practice, particularly with respect to selection of curing methods. This does not infer that poor construction practice was used, but rather that the focus was on achievable, practical implementation.

By then using the durability index tests to measure potential durability (control) and achieved durability (site-curing methods) it would be possible to evaluate the validity of the laboratory findings in a practical site situation. It would also be possible to ascertain if the durability index tests were valid in a practical site situation and also the effectiveness of various site-curing methods utilized.

2.18.2 OBJECTIVES OF PROJECT

- To broadly comment on the validity of the durability index tests when used in a real site situation;
- To determine the relative effectiveness of various site-curing methods in terms of producing durable concrete;
- To provide test elements to add to a database of results and also to expand our current understanding of mechanisms and measures to ensure durable concrete; and
- To make recommendations as to further work required in moving closer to the ultimate goal of developing a durability specification.

2.18.3 LAYOUT OF THESIS

Chapter 3 discusses the experimental details of the project, outlining the location of the test sites and the experimental procedures used. At the outset of the project is was decided to use the testing facilities at the University of Cape Town, and not to establish a laboratory on-site. Thus the University staff and not the writer undertook the various test. The use of core and cube compressive strength was used to perform a quality control function only, and it is outside of the scope of this project to investigate the factors that influence the strength development. This chapter also sets out a section detailing the statistical analysis of the data to establish the presence of outliers.

Chapter 4 sets out a characterisation framework used to quantify the various environmental effects on the various site cured concrete elements. This is crucial to this project given that it was undertaken in an uncontrolled environment. Chapters 5 to 7 discuss the various durability index results culminating in a general conclusion and some thoughts on the way forward.

CHAPTER 3

EXPERIMENTAL DETAILS

3.1 LOCATION OF EXPERIMENTAL SITES

The two test sites are located in the Port of East London at the mouth of the Buffalo River as shown on the 1:10 000 locality plan in Appendix 1. Test Site No. 1 (slabs) is ~ 20 m from the high-water mark and can be characterised as being in a severe exposure site subjected to salt spray but no wave action. Test Site No. 2 (walls) is ~ 2 km from the mouth of the river and can be considered to be less exposed.

Test Site No. 1 (slabs) has its East, South and West faces unobstructed while the North face is ~ 10 m from a 1,8 m high precast concrete boundary fence. This might offer some shielding, however this is probably minimal. Test site No. 2 (walls) has its North, South and Western faces exposed while the East face is ~ 50 m from a 1,8 m high precast concrete fence. In this case it is plausible that this could have a shielding effect. The grass adjacent to the test site is also lush and given the height of the walls could also offer some degree of shielding.

3.2 SITE WORK

3.2.1 NUMBER AND TYPE OF TEST ELEMENTS

The author was employed in the Port of East London as a Clerk of Works on an R80m project involving placing of ~ 2700m² of mass concrete paving and various new buildings. The initial intention was to use two elements of the project as a research test site viz. the mass concrete paving and reinforced concrete retaining wall (see Photographs 6 & 7 in Appendix 2). It was decided after due consideration to rather construct two individual test elements adjacent to or in the area of the originally anticipated structures. Given that the project extended virtually a full year it was decided to cast four sets of slab elements each cured under various seasonal conditions.

3.2.2 MIX DESIGNS AND BINDER TYPES

At the outset of the project it was decided to use three extender blends, namely OPC/GGBS, OPC/FA and OPC/CSF for both the walls and slabs. For the slab series a target strength of 44 MPa was used based on a characteristic strength of 35 MPa @ 28days, while for the walls a target strength of 35 MPa was used based on a characteristic strength of 30 MPa @ 28days. During the implementation of the project the cement manufacture specification (SABS 471) changed in South Africa resulting in the unavailability of "OPC" cement. Thus CEM I was used in various of the test elements. Table 8 and 9 indicate the mix proportions for the various test elements cast.

TABLE 8: MIX PROPORTIONS FOR WALL SERIES

MATERIAL DESCRIPTION	WALL A	WALL B	WALL C
Characteristic Compressive Strength @ 28 Days (MPa)	30	30	30
Target Compressive Strength @ 28 Days (MPa)	35	35	35
Target Slump (mm)	75	75	75
Water/Binder Ratio	0,50	0,50	0,57
19mm Dolerite Crushed Aggregate (kg/m³)	1230	1280	1200
Dolerite Crusher Dust kg/m³)	458	460	483
Pit Sand (kg/m³)	306	304	322
Extender (kg/m³)	190 GGBS	105 FA	20 CSF
Cementitious Binder (kg/m³)	190 OPC	240 OPC	320 OPC
Water (mℓ/m³)	190	180	195
P 509 Plasticiser (mℓ/m³)	Nil	Nil	1,120

TABLE 9: MIX PROPORTIONS FOR SLAB SERIES

MATERIAL DESCRIPTION	SLAB A		SLAB B		SLAB C	
	1&2	3&4	1&2	3&4	1&2	3&4
Characteristic Compressive Strength @ 28 Days (MPa)	35	35	35	35	35	35
Target Compressive Strength @ 28 Days (MPa)	44	44	44	44	44	44
Design Target Slump (mm)	75	75	75	75	75	75
Water/Binder Ratio	0,46	0,46	0,47	0,47	0,54	0,54
19mm Dolerite Crushed Aggregate (kg/m³)	1230	1230	1280	1280	1200	1200
Dolerite Crusher Dust kg/m³)	438	438	422	422	457	457
Pit Sand (kg/m³)	292	292	281	281	305	305
Extender (kg/m³)	209 GGBS	209 GGBS	115 FA	115 FA	24 CSF	24 CSF
Cementitious Binder (kg/m³)	209 OPC	209 CEM I	265 OPC	265 CEM I	340 OPC	340 CEM I
Water (mℓ/m³)	190	190	180	180	195	195
P 509 Plasticiser (mℓ/m³)	Nil	nil	nil	nil	1,190	1,190

Table 10 indicates the results of a physical chemical analysis of all the various binder materials used for production of concrete for this project, including both the OPC and CEM I materials. The reported fineness of the CEM I cement appears to be very high (very fine). Alpha Laboratories undertook the chemical analyses on cementitious material from site. In subsequent communications with the Alpha Laboratories they indicated that the mean fineness for the OPC cement for the period 01 May 1997 to 31 July 1997 was 414 kg/m² with a minimum of 367 and a maximum of 479 kg/m². They also indicated that the mean fineness for CEM I cements for the period 01 August 1997 to 31 December 1997 was 379 kg/m² with a minimum of 358 kg/m² and a maximum of 400 kg/m². Clearly the fineness data for the OPC cement as presented in Table 10 below is questionable. The possible cause for this is due to the presence of hydrated lumps in the sample, which will effect the Blaine fineness determination. Thus fineness will not be considered in further discussions in this document.

TABLE 10: CHEMICAL ANALYSIS OF CEMENTITIOUS MATERIALS USED FOR PROJECT *(AS REPORTED BY ALPHA GROUP CEMENT LABORATORY, JANUARY 1998)*

	Chemical Analysis (%)				
Clinker Constituents	**Portland Cement**		**Extenders**		
	OPC	**CEM I**	**GGBS**	**FA**	**CSF**
CaO	64,58	66,21	32,66	4,83	0,68
SiO_2	20,95	21,44	38,47	51,00	86,41
Al_2O_3	3,73	3,71	14,15	33,36	1,93
MgO	1,73	1,82	10,56	1,19	0,58
TiO_2	0,24	0,25	0,89	1,66	0,06
Fe_2O_3	2,50	2,67	0,85	3,51	1,73
Mn_2O_3	1,04	0,96	1,03	0,03	0,11
K_2O	0,55	0,58	0,90	0,60	1,33
$Na_2O^{\#}$	0,00	0,00	0,03	0,08	0,13
$SO_3^{\#}$	0,00	0,00	0,25	0,00	0,00
Cr_2O_3	0,03	0,03	0,02	0,09	0,05
$P_2O_5^{\#}$	0,09	0,08	0,01	0,35	0,11
LOI *	3,70	1,70	0,15	1,30	4,20
TOTAL	99,13	99,44	99,97	98,05	97,38
Fineness (Blaine) (kg/m^2)	297	390	356	No result	No result

*LOI represents loss on ignition and is the loss in mass caused by material vaporised during the heating of the sample.
Not accurate due to fused bead.

3.2.3 CASTING DETAILS

3.2.3.1 Wall Series

For the wall series timber shutters were used, see Photographs 4 and 5 in Appendix 2 for a visual presentation of the wall series.

The concrete was site batched using a portable 310 ℓ mixer and the dry material proportions were determined by the use of a mass balance (see Photograph 9 in Appendix 2). The amount of water added was controlled by the use of a slump cone (see Photograph 10 in Appendix 2). The exposed surface of the concrete was struck-off using a wooden float. For details of casting dates and striking of formwork refer to Table 11.

3.2.3.2 Slab Series

In this case steel shutters were used (see Photograph 8 in Appendix 2), to cast panels. See Photographs 1, 2 and 3 in Appendix 2 for a visual presentation of the slab series. The concrete production was as for the wall series.

The surface of the slab was levelled using an aluminium "straightedge" and then wood float finished. When bleeding had ceased and the surface was sufficiently hardened the surface was broomed using a builder's block brush. Finally the panel was split into four quadrants using a nosing tool (see Photographs 11 and 12, Appendix 2).

TABLE 11: CASTING AND CURING DETAILS FOR ALL TEST ELEMENTS

	CAST	CORING (1st)	CORING (2nd)	STRIP FORMS	CURING APPLIED			CURING REMOVED		
					C	F	H	C	F	H
WA	30-04-97	29-05-97	10-10-97	01-05-97	01-05	30-04	01-05	-	05-05	05-05
WB	13-05-97	16-06-97	10-10-97	14-05-97	14-05	13-05	14-05	-	18-05	18-05
WC	20-05-97	17-06-97	10-10-97	21-05-97	21-05	20-05	21-05	-	25-05	25-05
					C	S	H	C	S	H
SA1	07-05-97	07-06-97	22-10-97	08-05-97	07-05	07-05	07-05	-	11-05	11-05
SA2	27-06-97	27-07-97	16-11-97	28-06-97	27-06	27-06	27-06	-	02-07	02-07
SA3	15-11-97	13-12-97	18-04-98	16-11-97	15-11	15-11	15-11	-	21-11	21-11
SA4	12-12-97	11-01-98	19-04-98	13-12-97	12-12	12-12	12-12	-	17-12	17-12
SB1	14-05-97	17-06-97	22-10-97	16-05-97	14-05	14-05	14-05	-	19-05	19-05
SB2	28-06-97	27-07-97	16-11-97	29-06-97	28-06	28-06	28-06	-	03-07	03-07
SB3	16-11-97	13-12-97	18-04-98	17-11-97	16-11	16-11	16-11	-	22-11	22-11
SB4	13-12-97	11-01-98	19-04-98	15-12-97	13-12	13-12	13-12	-	18-12	18-12
SC1	16-05-97	17-06-97	22-10-97	21-05-97	16-05	16-05	16-05	-	21-05	21-05
SC2	29-06-97	27-07-97	16-11-97	30-06-97	29-06	29-06	29-06	-	04-07	04-07
SC3	17-11-97	13-12-97	18-04-98	18-11-97	17-11	17-11	17-11	-	22-11	22-11
SC4	15-12-97	11-01-98	19-04-98	16-12-97	15-12	15-12	15-12	-	20-12	20-12

LEGEND

WA : Wall A
WB : Wall B
WC : Wall C

SA : Slab A
SB : Slab B
SC : Slab C

C : Curing Compound
F : Formwork
H : Hessian
S : Sand

Given that the aggregates were stored on-site (although covered with a tarpaulin), some concern was raised as to the possible contamination by chlorides. Thus samples of the fine fraction (crusher dust and pit sand) of the aggregates were sampled and analysed for Chloride content, by mass of aggregate. Fultons Concrete Technology[55] recommends a series of maximum chloride contents ranging from 0,05% to 0,20% (prestressed to marine reinforced concrete). The maximum chloride contamination measured was 0,00063% well below the recommended limit.

Figure 8 shows the results of the analyses and represents the chloride content as a percentage of the dry mass of aggregate sample.

3.2.4 CURING METHODS

The choice of curing method to be used was largely governed by existing site practice used in the industry. Given the practical nature of the project it was imperative that the curing methods selected were both practical (easy to use), cheap and common to the construction industry.

After some deliberation the following curing methods were selected. As a means of control, curing of the samples in a temperature-controlled bath was the benchmark curing method. It was decided to use the specification relative to curing of cubes for compressive strength determination given its widespread use and acceptance in the industry. In addition to this four "site-curing" methods were selected each as described in detail below.

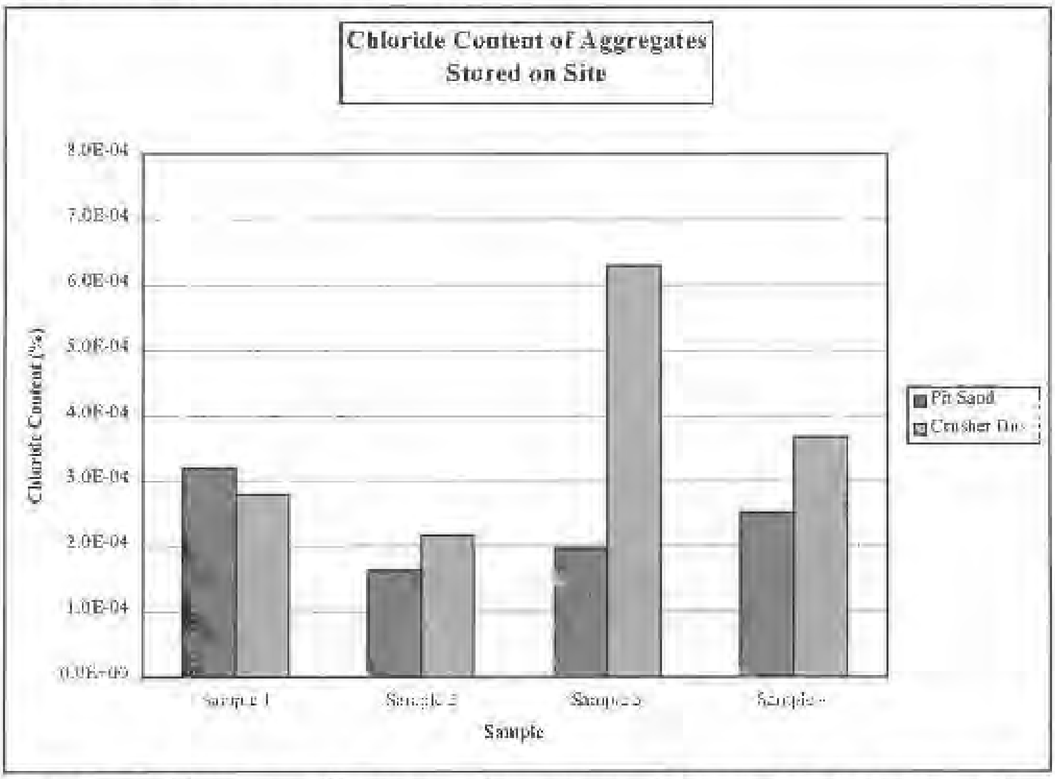


FIGURE 8: MEASURED CHLORIDE CONTENT OF AGGREGATES STORED ON-SITE, USED TO MANUFACTURE TEST ELEMENTS

The curing period selected on-site varies from that specified in SABS 1200G. SABS 1200G calls for seven days of continuous curing when using GGBS and also requires sand or hessian to be kept continuously wet. It is well established from review of current literature[3 16 17] that the guidelines have no rational basis, and in addition to this, Griesel's[10] work indicated that three days of wet curing was optimal from a practical aspect. In addition, there is literature[3] supporting the notion that even on construction sites with excellent quality control, curing to SABS 1200G requirements is rarely carried out. Most construction sites practise moisture-retention curing rather than moisture addition curing. Based on the above observations the reduced curing time was selected to represent current implemented practice in a South African context.

3.2.4.1 No Curing

In this case the test elements were not cured at all. After striking of the shutters and finishing, the surface was simply exposed to the elements.

3.2.4.2 Curing Compound

This method of curing is probably the most common used in the industry. When selecting a product, input from the industry was obtained and it was decided to use a recognised brand name, being a pigmented resin-based compound. The compound was spray-applied using the application rates suggested by the product supplier. Table 11 details the application time of the compound for each test element. In the case of the walls the compound was applied on striking of the formwork, and the slabs as soon as bleeding ceased and finishing was complete.

3.2.4.3 Hessian

This curing method is commonly specified but requires a considerable amount of effort to apply effectively. In practice the hessian is normally covered with a plastic sheet (not black) to prevent moisture evaporation. The hessian was applied in a double layer, saturated and thoroughly covered with a green 150 mm plastic sheet. Table 11 details when the hessian was applied and also when it was removed. The minimum curing period used was five days, however due to practical constraints this did vary.

3.2.4.4 Formwork Retention

This method was used for the walls only and the timber shutters were left in place after casting and struck after a minimum of five days (refer Table 11 for details).

3.2.4.5 Sand

This method was used for the slabs only, and was selected due to its common use in the industry for slab construction. A ~ 75mm layer of sand was applied to the concrete surface after bleeding stopped and finishing was complete. The sand was then thoroughly saturated and left for a minimum of 5 days. No subsequent wetting was undertaken in summer and the sand was simply removed after the curing period (see Table 11 for details).

3.2.5 CORING DETAILS

3.2.5.1 Equipment

Coring equipment supplied by a local materials laboratory was used (refer to Photograph 19 in Appendix 2 for a full explanation of the operation details etc).

3.2.5.2 Procedure

The procedure for coring was as follows:

- The core positions were marked using red wax crayon, and the cores numbered on the coring surface;
- The equipment was set-up and 68 mm diameter cores were extracted as detailed in Table 12; (the slab elements were cored in the direction of placing, while the walls and cubes (control) were cored perpendicular to the direction of casting).
- The cores were removed using a 4 lb. hammer and cold steel chisel;
- The cores were then carefully inspected for defects (cracks, large voids etc). If a core exhibited noticeable defects it was discarded and another core was extracted; and
- The cores were marked using masking tape, packaged by wrapping in newspaper and then sent to the University of Cape Town via road freight for testing.

TABLE 12: DETAILS OF CORES EXTRACTED

	AGE (DAYS)	NO.	LENGTH (MM)	DI AND MATERIAL TESTING			
				Cl	WS	OPI	fc
TEST ELEMENTS	28	4	~ 150		√	√	√
	28	4	~ 80	√			
	120	3	~ 150		√	√	√
	120	3	~ 80	√			
CUBES	28	4	150	√	√	√	√
	120	4	150	√	√	√	√

LEGEND:
Cl : Chloride Conductivity
WS : Water Sorptivity
OPI : Oxygen Permeability Index
fc : Core Compressive Strength

3.2.6 CUBE AND CORE COMPRESSIVE STRENGTH DETAILS

Cubes were cast at the same time as the various test elements, using the same concrete, and cured in a temperature-controlled curing bath at a constant temperature of 23°C (as set out in SABS Method 863)[46] for two reasons viz.

- As a means of determining the potential durability of each test element; (this was done by extracting cores from the cubes at both 28 and 120 days and using the cores as a control)
- As a means of compressive strength quality control.

On coring each of the test elements, cores were extracted from the cubes for compressive strength determination, per curing method. The primary questions regarding compressive strength data are:

- Did each of the test elements meet the design cube compressive strength at 28 days?; and
- What is the range of cube results at 28 and 120 days, and do the core compressive strengths mirror this trend?

In assessing the outcome only the cores extracted from 28 and 120-day water cured cubes and cube compressive strengths are evaluated. While Figures 9 and 10 show the summary of all core compressive strengths (site cured elements also), this is for completeness only. It is beyond the scope of this study to examine the influence of curing method on potential core compressive strength.

The core compressive strengths were determined by accurately trimming and grinding the ends and recording the failure load. The length was always equal to a minimum of 1,0 times the diameter. No allowance was made for curing history (site cured elements), direction of curing or percentage air voids, as recommended by SABS Method 865. Four core tests were used per test determination. It is worth noting that SABS Method 865 requires a minimum core diameter of 100mm for compressive strength determination, although it is generally accepted that a core diameter of at least three times the largest aggregate fraction will suffice (personal communication with Alexander). SABS Method 865 indicates that cores of smaller diameter can yield higher results.

Considering the wall test elements (the results are indicated in Figure 9 on page 46), the target cube compressive strength at 28 days was required to be 35 MPa. The cube results of all of the concrete types (GGBS, FA and CSF) exceed this limit and the CSF concrete exhibits noticeably higher cube compressive strength at 28 days (~ 53 MPa) when compared to the GGBS and FA concrete (~ 36 MPa). This is also true for the core compressive strengths for wet-cured cubes at 28 days. However the core compressive strengths for FA concrete are noticeably higher than the cube compressive strengths (~ 46 MPa vs. ~ 36 MPa), while the CSF and GGBS concrete exhibits remarkably similar cube and core compressive strength.

For the wall series no 120-day cube compressive strength data are available (refer to Section 3.4 of this chapter for a full explanation in this regard). However 60-day cube compressive strength data is available and of interest is how the strength has changed very marginally for CSF concrete from 28 days. The compressive strength of GGBS and FA concrete however has changed noticeably. The cube compressive strength for CSF concrete at 60 days is higher (~ 53 MPa) than the FA concrete (~ 47 MPa) and GGBS concrete (~ 44 MPa). The 120-day core compressive strengths indicate the same trend in terms of ranking of compressive strengths, however the strengths are noticeably higher when compared to the 60-day cube compressive strength results. Interestingly the core compressive strengths at 120 days fall within a very small band of between ~ 56 MPa and ~ 63 MPa.

Considering the above it can be concluded that the wall series met the 28 characteristic cube compressive strength. While the 28-day cube compressive strengths indicated CSF concrete as having a noticeably higher strength grade, at 120 days the compressive strength has equalised indicating concretes of very similar strength grade.

Considering the OPC binder concrete slab series test elements (the results are indicated in Figure 10 on page 47), the target cube compressive strength at 28 days is 44 MPa. The cube results of all of the concrete types (GGBS, FA and CSF) are very close to or exceed this limit and the CSF concrete exhibits a higher cube compressive strength at 28 days (~ 53 MPa) when compared to the GGBS and FA concretes (~ 45 MPa). This is also true for the core compressive strengths at 28 days, however all the concretes exhibit larger core than cube compressive strengths.

As for the wall series no 120-day cube compressive strength data are available (refer to Section 3.4 of this chapter for a full explanation in this regard). However the 60 day cube compressive strength indicates the same trend as for 28-day results.

The 120-day core compressive strengths indicate the CSF and FA coincide in a similar strength range (~ 65 MPa) with the GGBS concrete lower (~ 55 MPa).

Considering the CEM I binder concrete slab series test elements (the results are indicated in Figure 10), the target cube compressive strength is 44 MPa. All of the concrete types (GGBS, FA and CSF) are very close to or exceed this limit and the CSF concrete exhibits a noticeably higher cube compressive strength at 28 days (~ 55 MPa) when compared to the GGBS and FA concretes (~ 45 MPa). This is also true for the core compressive strengths at 28 days, however all the concretes exhibit larger core compressive strengths.

The trend noticed for the 28-day cube compressive strengths is repeated at 120 days with a noticeable increase in cube compressive strength from 28 to 120 days. The CSF and FA concretes exhibit a similar cube compressive strength (~ 63 MPa) at 120 days with the GGBS concrete lower (~ 53 MPa).

For the core compressive strength at 120 days the trend is repeated and indicates the CSF and FA concrete are in a similar strength range (~ 73 MPa) with the GGBS concrete marginally lower (~ 65 MPa). Considering the above it can be concluded that the CEM I binder concrete slab series met the 28-day characteristic cube compressive strengths.

Table 13 below indicates the cube compressive strength gain with time for the slab elements cast using both OPC and CEM I cements. Based on the chemical analysis as presented in table 7 above, it is anticipated that given the similar clinker chemical composition and increased fineness of the CEM I that it will result in higher earlier age strength gain. From the results in Table 13 this is not evident and the plausible explanation is that the various extenders have had the effect of masking the fineness of the CEM I. It is also possible that the raw materials for the OPC and CEM I are from two different sources, although from the same supplier.

TABLE 13: DETAILS OF CUBE COMPRESSIVE STRENGTH VS. ELEMENT AGE

			CUBE CHARACTERISTIC STRENGTH		
		TEST ELEMENT	**fcu @ 7 days (MPa)**	**fcu @ 14 days (MPa)**	**fcu @ 28 days (MPa)**
GGBS	**OPC**	**SA1**	30,6	40,8	45,1
		SA2	27,5	37,4	44,1
	CEM I	**SA3**	31,5	36,7	43,4
		SA4	25,3	38,6	45,0
FA	**OPC**	**SB1**	27,5	35,8	42,5
		SB2	29,3	37,7	45,3
	CEM I	**SB3**	31,5	37,1	45,2
		SB4	25,8	36,7	41,5
CSF	**OPC**	**SC1**	41,6	46,2	52,5
		SC2	38,6	46,5	52,7
	CEM I	**SC3**	38,3	44,2	50,8
		SC4	34,0	43,8	51,9

3.3 LABORATORY WORK

3.3.1 DURABILITY INDEX TESTS FOR CONCRETE

The details pertaining to scope, test method, significance, apparatus, sample preparation and conditioning and test procedures for the three durability index tests are covered in detail in a document published by the University of Cape Town[33]. These details are thus not repeated in this document.

3.3.2 DATA GENERATION

3.3.2.1 Cube Compressive Strength

The cube compressive strength was determined by using equipment locally available at a materials laboratory in East London. Appendix 3 shows the format in which the data are recorded on a worksheet. In this case a single worksheet represents the full range of data per test element.

3.3.2.2 Core Compressive Strength

The core compressive strength was determined in the Civil Engineering laboratory at the University of Cape Town and sent to the author by electronic format and hard copy. Appendix 4 shows the format in which the data is recorded on a worksheet. In this case a single worksheet represents the full range of data per test element at a given age.

3.3.2.3 Chloride Conductivity

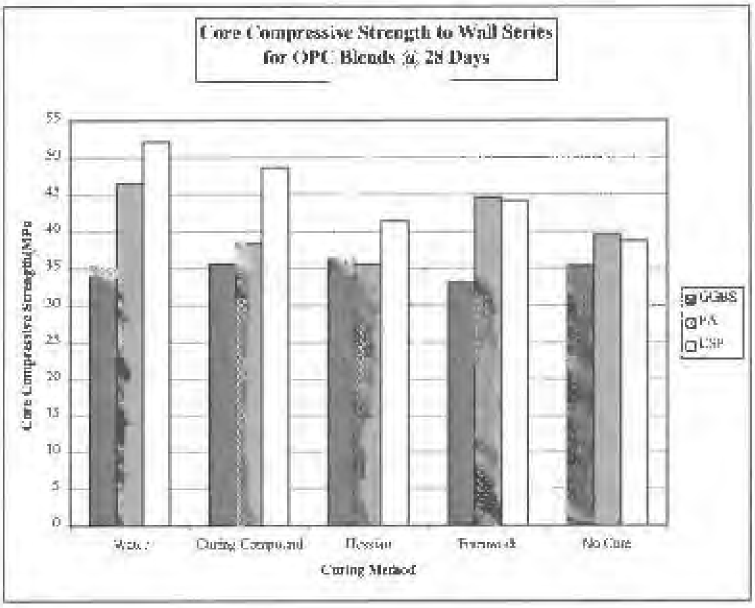
The chloride conductivity was determined in the Civil Engineering laboratory at the University of Cape Town and sent to the author by electronic format and hard copy. Appendix 5 shows the format in which the data is recorded on a worksheet. In this case a single worksheet represents the full range of data per test element at a given age.

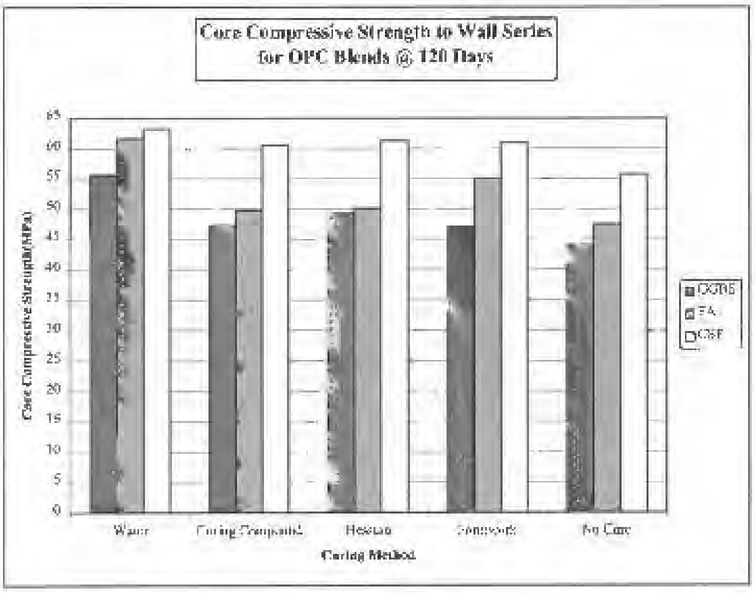
3.3.2.4 Water Sorptivity

The water sorptivity was determined in the Civil Engineering laboratory at the University of Cape Town and sent to the author by electronic format and hard copy. Appendix 6 shows two spreadsheets indicating the format in which the data is recorded. In this case it is necessary to have six separate spreadsheets per test element at a given age. Five spreadsheets per curing method and a summary of the data are included.

3.3.2.5 Oxygen Permeability Index

The oxygen permeability index was determined in the Civil Engineering laboratory at the University of Cape Town and sent to the author by electronic format and hard copy. Appendix 7 shows two spreadsheet indicating the format in which the data is recorded. In this case it is necessary to have six separate spreadsheets per test element at a given age. Five spreadsheets per curing method and a summary of the data are included.





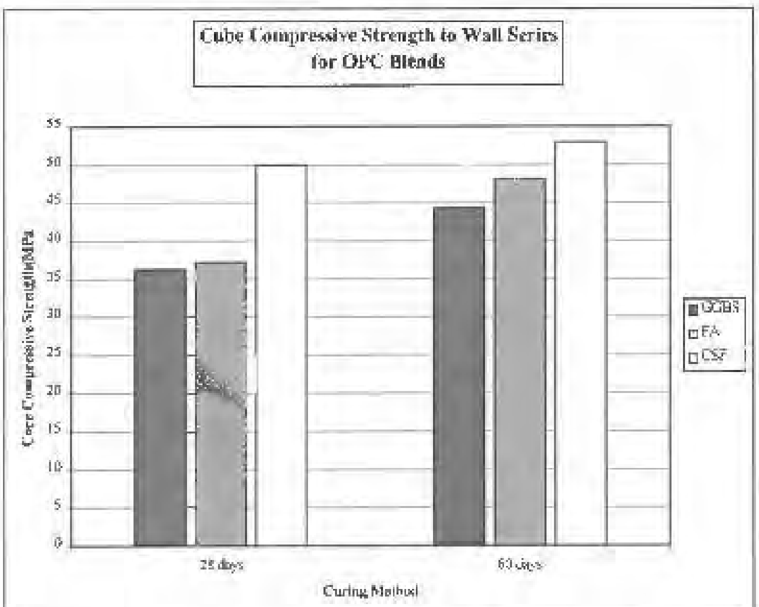


FIGURE 9: SUMMARY OF CUBE AND CORE STRENGTH RESULTS FOR WALL SERIES

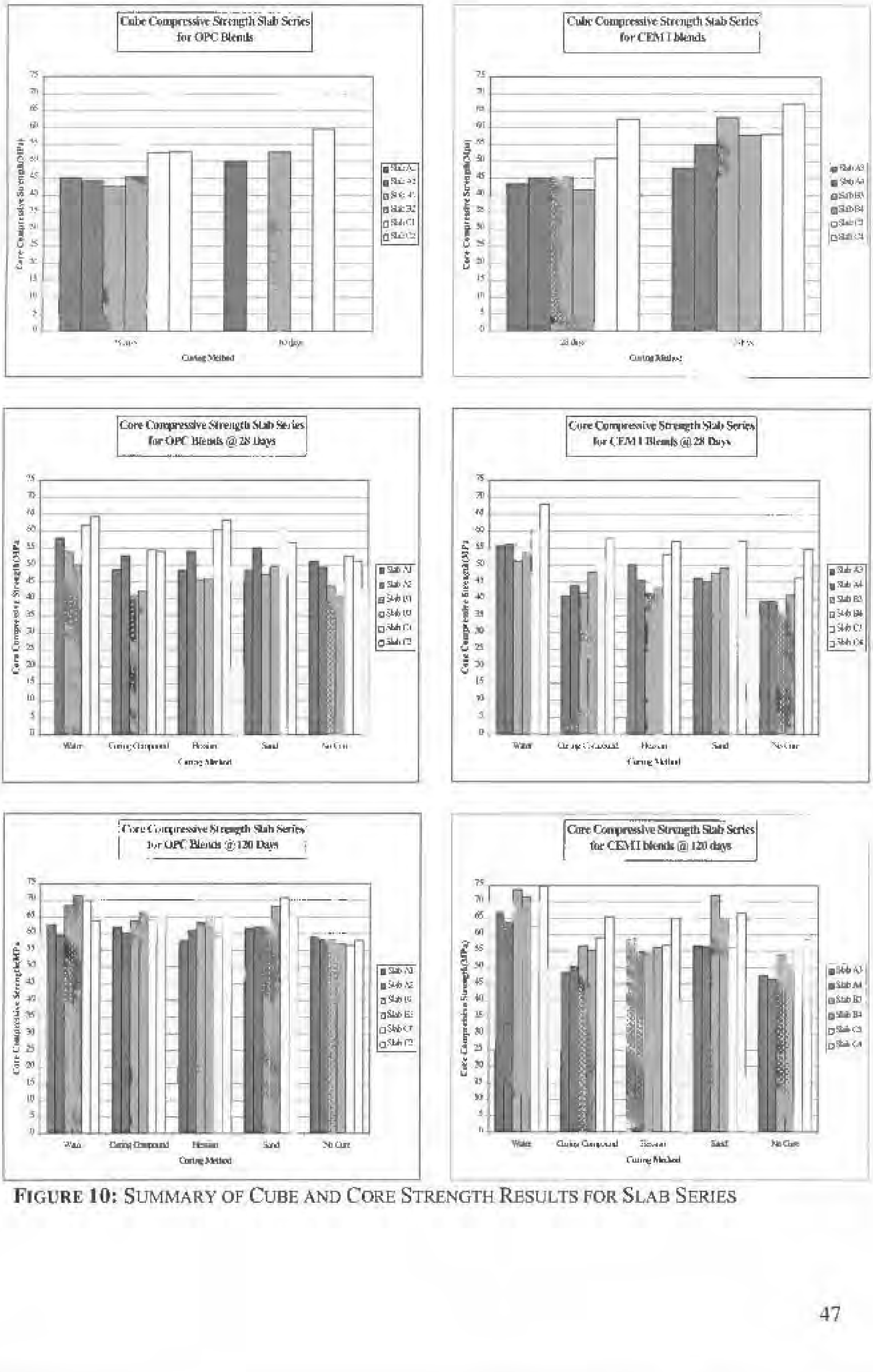


FIGURE 10: SUMMARY OF CUBE AND CORE STRENGTH RESULTS FOR SLAB SERIES

3.3.3 QUALITY CONTROL PROCEDURE

The American National Standards (ANS) publication "Standard Practice for Dealing with Outlying Observations" Designation: E178 – 80 (Re-approved 1989) was used as a means of evaluating the statistical variability of the data. Section 4.1 and 4.2 of the publication has been reproduced in Appendix 8 for reference. A 5% significance level was used in the evaluation and data found to be outside the significance level window was discarded. Each determination was evaluated in the processing of the raw data as received from the laboratory.

The full data for each set of the durability indexes was also evaluated using the same ANS publication. This was done for both the wall and slab series per binder type. Appendices 10 to 18 show the detail of the full data set statistical analyses, (three per durability index, thus a total of nine). The analysis groups element type (wall or slab), binder type, element age and curing method for the first statistical evaluation. Since the walls only have one final result per curing method, they are not evaluated with the first evaluation. A second evaluation is also undertaken grouping element type, binder type and element age (in other words all the curing methods are considered part of the same population). It must be noted that this is not strictly statistically correct, but is a useful tool in evaluating the spread of results. No data considered anomalous is discarded from this evaluation, it is simply used as a useful comparative analysis tool.

3.3.3.1 Chloride Conductivity

Appendix 10 details the statistical analysis of the GGBS concretes for walls and slabs per curing method at 28 and 120-day element ages. A broad analysis of the wall series data, across the range of curing methods, indicates that all the data lies within the statistical variability considered acceptable with no anomalies noted. The same is true for the analysis of the slab series data. A more detailed analysis of the slab series data, across the range of curing methods, also indicates that no anomalous data is present.
Result: No data from this set to be considered anomalous.

Appendix 11 shows the same as above but for FA concretes. An evaluation of the slab series per curing method indicates that the result to SB2 for 28-day water curing (1,43 mS/cm) is anomalous (too high). A broader analysis of the entire set of slab results across the range of curing methods does not confirm this but this is expected given the larger population. It must be borne in mind that the grouping of the results across curing methods is strictly speaking statistically incorrect, but useful as a guide. A broad analysis of the wall data indicates that the result to WB for 120-day water curing (0,17 mS/cm) is anomalous (too low). In this case however it must be noted that this observation is relative to grouping all the data across the range of curing methods, and the FA concretes exhibit extreme sensitivity to wet curing. The results for 120-day wet curing for the OPC/FA concrete slab series (0,12 mS/cm and 0,17 mS/cm) are very similar to the result in question thus it would appear in this case that the weight of evidence suggests that the result is not anomalous.
Result: Result for SB2 for 28-day water curing considered to be anomalous, hence rejected from further discussions and evaluation.

Appendix 12 details the statistical analysis of the CSF concretes. Both the analyses indicate that the data set does not indicate any anomalous data.
Result: No data from this set to be considered anomalous.

3.3.3.2 Water Sorptivity

Appendix 13 details the statistical analysis of the GGBS concretes for walls and slabs per curing method at 28 and 120-day element ages. A detailed evaluation of the slab series per curing method indicates that the 120-day result for SA2, hessian curing (2,40 mm/√h) is anomalous (too low). A broader analysis of the entire set of slab results across the range of curing methods also confirms this.
Result: 120-day result for SA2, hessian curing, considered to be anomalous, hence rejected from further discussions and evaluation.

Appendix 14 details the statistical analysis of the FA concretes. The broad analysis of the wall series data, across the range of curing methods, indicates that all the data lie within the statistical variability considered acceptable with no anomalies noted. The same is true for the broad analysis of the slab series data. A more detailed analysis of the slab series data, across the range of curing methods, also indicates that no anomalous data are present.
Result: No data from this set to be considered anomalous.

Appendix 15 details the statistical analysis of the CSF concretes. The broad analysis of the wall series data, across the range of curing methods, indicates that all the data lie within the statistical variability considered acceptable with no anomalies noted. The same is true for the broad analysis of the slab series data. A more detailed analysis of the slab series data, across the range of curing methods, also indicates that no anomalous data are present.
Result: No data from this set to be considered anomalous.

3.3.3.3 Oxygen Permeability

For the statistical evaluation of the oxygen permeability data the D'Arcy coefficient of permeability was used and not the OPI.

Appendix 16 details the statistical analysis of the GGBS concretes for walls and slabs per curing method at 28 and 120-day element ages. A detailed evaluation of the slab series per curing method indicates no anomalies. The same is true for the wall series and a more general evaluation of the data.
Result: No data from this set to be considered anomalous.

Appendix 17 details the statistical analysis of the FA concretes. A detailed evaluation of the slab series per curing method indicates that 28-day result for SB4, no curing (OPI 9,58) is anomalous (too low). A broader analysis of the entire set of slab results across the range of curing methods contradicts this but is expected given the larger population. These broader analyses reveals that the 28-day result for SB4, curing compound (OPI 9,28) curing is anomalous (too low). A detailed analysis was not possible for this curing method since only two results were recorded.
Result: 28-day result for SB4, no curing, considered to be anomalous, hence rejected from further discussions and evaluation.

Appendix 18 details the statistical analysis of the CSF concretes. A detailed evaluation of the slab series per curing method indicates that 28-day result for SC2, hessian curing (OPI 9,95) is anomalous (too high). It also indicates that the 120-day result for SC2, sand curing (OPI 10,00) is anomalous (too high). A broader analysis of the entire set of slab results across the range of curing methods contradicts this but is expected given the larger population.
Result: 28-day result for SC2, hessian curing, and 120-day result for SC2, sand curing, considered to be anomalous, hence rejected from further discussions and evaluation.

3.3.4 LIMITATIONS AND OTHER CONSIDERATIONS

At the outset of the project the initial intention was to undertake the index testing at 28 days. When the first data was received, some anomalies were noted. It was decided that cores would also be extracted at 120 days to attempt to establish the cause of the anomalies. A 120-day coring age was chosen because firstly it was at about this time in the project that it became clear that the first data indicated anomalies. Secondly it was also at this time that information became available in the larger S.A. research effort that indicated that currently used extenders take longer than 28 days to develop their potential durability characteristics. Thirdly it was at the time indicated to the author (personal communication Alexander), that concrete pavements in Belgium were only evaluated for durability performance at three months (~90 days) age.

To facilitate coring at 120 days and core strength determination of cubes at 120 days, it was necessary to allocate two cubes for compressive strength determination at 7, 14, 28 and 120 days. This is not as recommended by SABS Method 863, which specifies a minimum of three cubes to be crushed per compressive strength determination.

Due to the number of cubes remaining at the time the decision was made to core at 120 days, it was unfortunately not possible to determine the cube compressive strength at 120 days for the wall series test elements or for the OPC binder concretes (series 1 and 2 slabs). It was subsequently established that irregularities in the laboratory procedures resulted in the noted anomalies. These results have been isolated and where relevant in this document noted as being unreliable. Note that this unforeseen change resulted in a large increase in workload. It also added a further variable. However the author is of the opinion, that the determination of the durability indexes at 120 days has been invaluable in terms of the understanding it has added to this project.

A CD-ROM is attached to the thesis containing all of the test data in spreadsheet format, given that the volume of information if appended, will make the document unwieldy and cumbersome.

CHAPTER 4

DEVELOPMENT OF AN ENVIRONMENTAL CHARACTERISATION SYSTEM

4.1 GENERAL INTRODUCTION

The hydration reaction in cement can only proceed with sufficient available moisture in the "young" concrete, which in turn influences properties such as porosity, permeability and diffusivity of the concrete. These properties influence the rate of penetration of aggressive agents that may cause corrosion damage to the steel reinforcing bars. It is well established that the rate of hydration is very sensitive to the relative humidity of the pores in the concrete[30], thus the rate of moisture loss can significantly influence the development of the properties of the covercrete - the thin skin of concrete situated between the reinforcing and the surface of the concrete, typically 20 to 50 mm thick.

Environmental factors such as temperature, relative humidity and precipitation all influence the evaporation of pore water and thus play a role in the moisture exchanges of the covercrete. This in turn affects the properties of the cement paste responsible for ensuring the material's resistance to the ingress of aggressive agents – broadly referred to as durability.

As mentioned previously the nature of the research project was such that the environmental conditions varied in an uncontrolled manner for the duration of the project. While evaluation of the effects of the climate on the various durability indexes was not the primary aim of this project, such effects remain a crucial issue, requiring thought and some means of quantifying their effect on concrete durability.

The objective of this chapter is to suggest a framework for a broad environmental characterisation system. This suggested framework is based on the limited data available, and is an area where considerable additional research work is justified. The aim of the system is to assist with interpreting the durability index results and also to broaden the understanding of the variability of the results.

4.2 UNDERLYING PRINCIPLES OF ENVIRONMENTAL CHARACTERISATION SYSTEM

This section details the development of the individual steps of the characterisation system together with the underlying principles and limitations of each step of the procedure.

At the outset it must be stressed that this is a preliminary, broad characterisation system and the focus is on achieving a holistic, relative understanding of the environmental effects on the test results. Nevertheless, an effort has been made to produce realistic models that can form the basis for future refinement of the characterisation system.

The steps in the development of the system are outlined in broad detail immediately below and the procedure is explained in greater detail subsequently in this chapter.

STEP 1: DEVELOPMENT OF THE IDEALISED ENVIRONMENTAL MODEL

The first step in applying a characterisation system of the environmental factors is to develop a model as a reference. The aim of the reference model is to assist with the evaluation of environmental effects on the durability indexes. An environmental model is developed for each of three environmental factors, namely temperature, relative humidity and precipitation. The various models show the effect of the environmental condition on the durability indexes i.e. water sorptivity, oxygen permeability and chloride conductivity.

STEP 2: DEVELOPMENT OF THE SCORING SYSTEM

The next step is to apply a scoring system, based on the environmental model, to quantify the effect of the particular environmental factors on the durability indexes measured. The scoring system will vary for the particular durability indexes.

STEP 3: COMBINING THE SCORING SYSTEM AND HYDRATION-RATE WEIGHTING SYSTEM

In the third step a weighting system is introduced to account for the change in hydration rate of the concrete with time. The applied weighting decreases with element age and varies for the three binders (as does the hydration rate). By combining the scoring and weighting system, the effect of the particular environmental factor (on the durability indexes) is aligned with the hydration rate of the binder under consideration.

STEP 4: APPLYING AN OVERALL WEIGHTING SYSTEM TO DEVELOP A FINAL ENVIRONMENTAL RATING

The final step in the process is to combine the scoring for the three environmental factors for a particular measured durability index, to yield an overall environmental rating. To do this it must be appreciated that for each of the three durability indexes the contribution of each of the three environmental factors will vary. For this reason an overall weighting is introduced to yield a single environmental rating. The final rating is compared to the "potential rating" – the rating for a fully water cured cube for that particular test element.

4.3 DEVELOPMENT OF THE ENVIRONMENTAL MODEL (STEP 1)

The development of the environmental model focuses on the three environmental influences or factors, namely temperature, relative humidity and precipitation. The development of each model is discussed separately together with its assumptions and limitations.

Griesel[10] studied the effect of temperature and relative humidity on the durability indexes and the models formulated here are based on his results. The study he undertook was limited to OPC - ordinary portland cement - as a binder and various combinations of temperature and relative humidity, which will be discussed in more detail in the section below. He also investigated the effects of different periods of wet curing and of concrete compressive strength on the durability indexes by considering concrete grades of 20, 40 and 60 MPa.

4.3.1 DEVELOPMENT OF IDEALISED TEMPERATURE MODEL

Griesel[10] used a constant relative humidity of 50%. By selecting temperatures of 18°C, 28°C and 35°C and periods of wet curing of 1, 3, 7 days respectively, he was able to relate the variation in measured durability indexes to a fully wet-cured 28-day condition.

Figure 11 shows the temperature model adopted for purposes of environmental characterisation for this project, based on Griesel's results. The model shows three temperatures i.e. 18°C, 28°C and 35°C with the percentage variation of the particular durability indexes measured by Griesel based on the 28-day water-cured result as the reference. The results on which the model is based are derived from a test condition having a relative humidity of 50%, a 1 day wet curing period and grade 40 MPa OPC concrete at an age of 28 days. (Note that the relative humidity and temperatures mentioned were effective after an initial 1 day period of wet-curing at 22°C and 100% relative humidity). The variation was determined relative to the 28-day water-cured results, and in the case of oxygen permeability k was used and not the OPI.

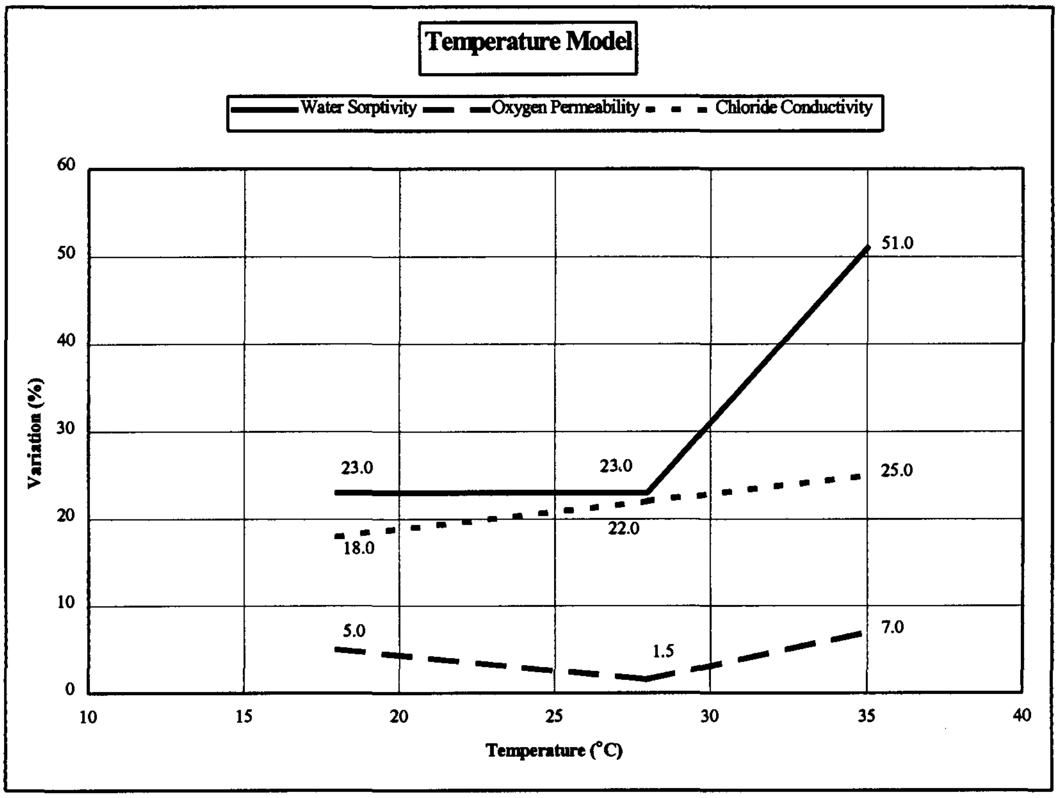


FIGURE 11: THE EFFECT OF TEMPERATURE ON THE DURABILITY INDEXES – AN IDEALISED MODEL USED TO DEVELOP A SCORING SYSTEM.

These limits were selected firstly since the 40 MPa concrete used by Griesel closely matched the strength grade of the test elements in this study (notwithstanding the difference in binder type). Secondly the relatively short 1 day wet curing period was selected so as to accentuate the effect of temperature (also this corresponds to practical conditions prevailing on many construction sites).

Thus, for example, for water sorptivity at 35°C and 50% relative humidity, a 1 day wet-cured grade 40 OPC concrete at 28-day would have a water sorptivity value 51% higher than the equivalent concrete wet-cured for 28 days at standard temperature (22°C).

4.3.2 Development of Idealised Relative Humidity Model

In another series of tests, Griesel[10] used a constant temperature of 18°C. By varying the relative humidity between 50%, 65% and 82% and the period of wet curing between 1, 3 and 7 days he was able to relate the variation in measured durability indexes to a 28-day wet-cured condition.

Figure 12 shows the relative humidity model adopted for purposes of environmental characterisation for this project. The model shows four relative humidity values i.e. 40%, 50%, 65% and 80% with the percentage variation of the particular durability indexes measured by Griesel based on the 28-day water-cured result as the reference. The results on which the model is based are derived from a test condition having a temperature of 18°C, a 1 day wet-curing period and grade 40 MPa OPC concrete. The 40% relative humidity results were obtained by extrapolating the 65% and 50% relative humidity results (measured at 28 days), which was reasonable within this relatively small range. (Note that the relative humidities and temperature mentioned were effective after an initial 1 day period of wet-curing at 22°C and 100% relative humidity, at 28 days).

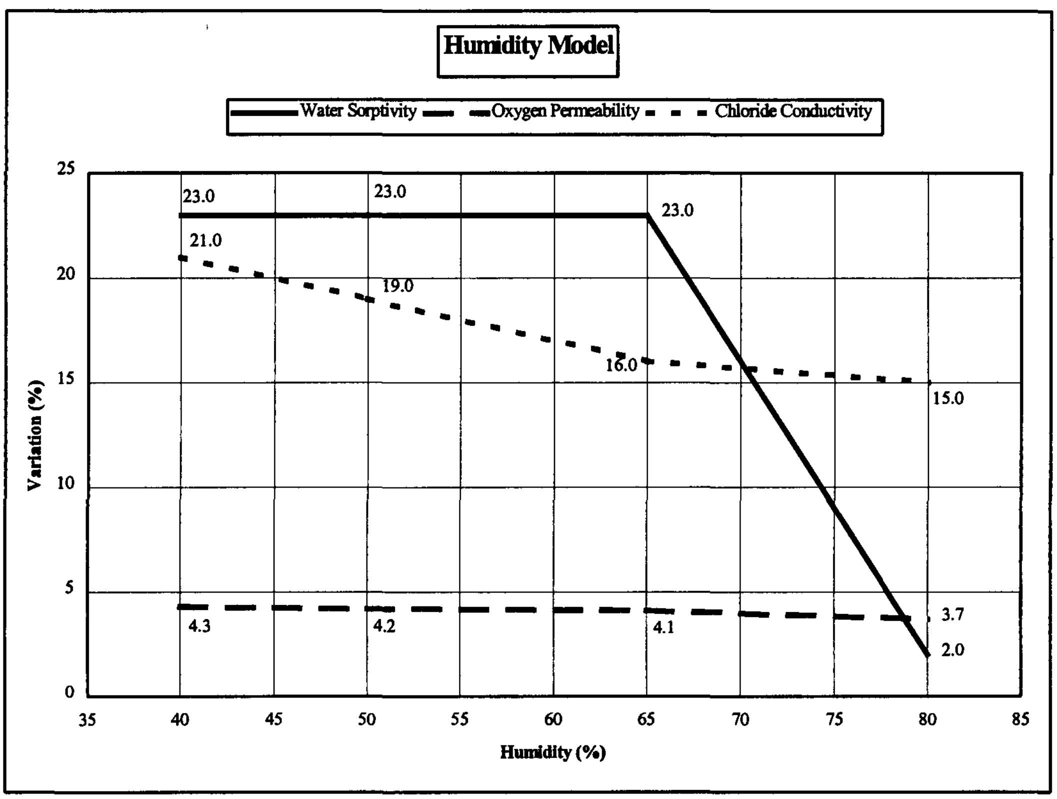


Figure 12: The Effect of Relative Humidity on the Durability Indexes – An Idealised Model Used to Develop a Scoring System.

Thus, for example, for water sorptivity at 18°C and 50% relative humidity, a 1 day wet-cured grade 40 OPC concrete would have a water sorptivity value 23% higher than the equivalent concrete wet-cured for 28 days at standard temperature (22°C) and a relative humidity of 100%, at 28 days.

4.3.3 DEVELOPMENT OF IDEALISED PRECIPITATION MODEL

Griesel[10] used three periods of wet curing, namely 1, 3, and 7 days for determining both the temperature and relative humidity effect on the durability indexes. Wet curing is taken to be the same as the effect of precipitation i.e. a wetted concrete surface.

Figure 13 shows the precipitation model adopted, from Griesel's work, for purposes of environmental characterisation for this project. The model shows three periods of wet curing i.e. 1, 3 and 7 days with the percentage variation of the particular durability index measured based on the 28-day water-cured result as the reference. The results on which the model is based are derived from a test condition having a relative humidity of 50%, a temperature of 18°C and grade 40 MPa OPC concrete at the age of 28 days. (Note that the relative humidity and temperature were effective after an initial period of wet-curing at 22°C and 100% relative humidity).

The no-curing results - 0 day wet curing - are not given but are anticipated to show a non-linear extrapolation from the 1 day period of wet curing. Data for the no-cure condition were not available from Griesel[10].

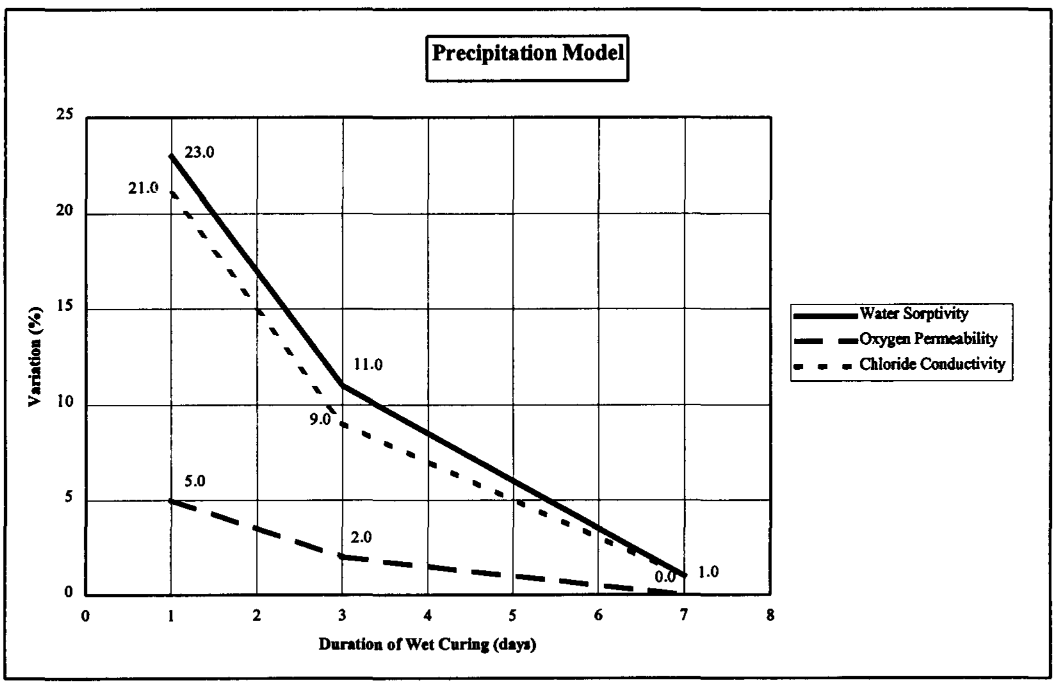


Figure 13: THE EFFECT OF PRECIPITATION ON THE DURABILITY INDEXES – AN IDEALISED MODEL USED TO DEVELOP A SCORING SYSTEM.

Thus, for example, for water sorptivity at 18°C and 50% relative humidity at the age of 28 days, a 1 day wet-cured grade 40 OPC concrete would have a water sorptivity value 23% higher than the equivalent concrete wet-cured for 28 days at standard temperature (22°C) and a relative humidity of 100%.

The limitations of these models are as follows:

- They are based on OPC as a binder while in this project three blended binders were used, namely OPC/GGBS, OPC/FA and OPC/CSF;
- The mean temperature range measured on the test site varied from 10°C to 25°C, while the temperature model makes allowance for a temperature range from 18°C to 35°C;
- The mean relative humidity range measured on the test site varied from 20% to 100%, while the relative humidity model makes allowance for a relative humidity range from 40% to 80%; and
- The results on which the models are based are derived from a test condition having a period of wet curing of 1 day, a relative humidity of 50% and a temperature of 18°C. The interaction of these various environmental factors will certainly influence the data - in other words the model is not a true reflection of a single environmental factor. The ideal scenario would be to have information based on a lower relative humidity - 10% to 20%, a lower temperature - 5°C to 10°C, and an uncured sample, to enable the individual environmental factors to be measured in isolation.

The limitations mentioned above and the absence of information on particular interactions must be borne in mind. Nevertheless the information available is useful and relevant to the construction of a broad preference framework.

4.4 DEVELOPMENT OF THE SCORING SYSTEM (STEP 2)

The purpose of the scoring system is to quantify the effect of the particular environmental factors on the durability indexes measured. Using the environmental models a scoring system is introduced as outlined in Table 14.

TABLE 14: SCORING SYSTEM FOR EACH ENVIRONMENTAL FACTOR RELATED TO THE DURABILITY INDEXES.

	ENVIRON. LIMITS	WATER SORPTIVITY SCORE	OXYGEN PERMEABILITY SCORE	CHLORIDE CONDUCTIVITY SCORE
TEMPERATURE	18°C	10	2	10
	28°C	10	10	6
	35°C	0	0	0
RELATIVE HUMIDITY	40 %	0	0	0
	65 %	0	4	8
	80 %	10	10	10
PRECIPITATION VOLUME	0 mm	0	0	0
	20 mm	5	5	5
	80 mm	10	10	10
PRECIPITATION DURATION	0 min	0	0	0
	310 min	6	7	7
	720 min	10	10	10

The scoring system is derived from the respective models (refer to Figures 11 to 13) as follows:

- For a given durability index the lowest variation is arbitrarily assigned the highest score - 10 - and the highest variation the lowest score – 0;
- The scoring at any point between these two limits is simply interpolated linearly using the range in variation as the base; and
- The scoring is rounded to the nearest whole number.

For precipitation the scoring is refined slightly as follows:

- The period of wet curing is related to precipitation volume and precipitation duration. The total maximum precipitation duration is 1440 minutes in a 24 hour period. However, continuous rainfall sustained for 24 hours seldom occurs. Furthermore, considering the manner in which precipitation duration data is recorded, it was felt more reasonable to adopt a maximum precipitation duration of 720 minutes per 24 hour period. The scoring for precipitation duration is adjusted in the same ratio as the wet curing duration; and
- The same procedure is used to assign a scoring system to precipitation volume, however in this case the maximum measured precipitation volume in a 24 hour period - 80 mm - is assigned the highest scoring. This was obtained from the rainfall records scrutinised over the duration of this project as obtained from the meteorological office at East London Airport.

4.5 DEVELOPMENT OF THE HYDRATION-RATE WEIGHTING SYSTEM (STEP 3)

The environmental effect on the various durability indexes must vary with time, based on the premise that the rate of the hydration reaction in concrete, which directly influences the properties of the covercrete, decreases with time. Thus, environmental effects can be expected to be far more critical and important in the earlier stages of the life of an element, particularly in the first few days after casting. It would therefore be sensible to divide the ages of an element into different periods, with greater weighting given to the earlier age periods. To develop a preliminary assessment of the possible weightings that can be assigned to element age periods, well-established data on the compressive strength gain of concrete with age, under fully water cured conditions, was used as a guide.

Compressive strength development does not necessarily correlate directly with development of the transport properties of the covercrete. In the absence of more conclusive data, it was considered that compressive strength used as a basis is reasonable, although there will be limitations in this approach. Depending on the type of binder used, the method of curing, and other factors the compressive strength gain of concrete fits broadly into the following categories[31] as indicated in Table 15. This guide is based on OPC and OPC Blends (in the respective proportions as used in this project) standardised with 120 days as the base.

TABLE 15: CHARACTERISATION OF CONCRETE STRENGTH GAIN WITH TIME FOR VARIOUS BINDER BLENDS (BASED ON DATA IN FULTON[31]).

AGE	PERCENTAGE OF 120-DAY STRENGTH AT GIVEN AGE (%)			
	OPC	OPC/GGBS BLEND	OPC/FA BLEND	OPC/CSF BLEND
3 DAYS	50	30	35	60
7 DAYS	70	50	50	80
14 DAYS	80	65	60	90
28 DAYS	90	80	70	95
90 DAYS	97	95	90	97
120 DAYS	100	100	100	100

Based on the data in Table 15 the weighting system as outlined in Table 16 is developed, by evaluating the weighting factor with respect to element age.

The limitations of the hydration rate weighting system are as follows:

- The weighting system is based broadly on the compressive strength gain of concrete with age. This is accepted as a starting point, but data is required for development of durability indexes with time; and
- The weighting system is assumed to be the same for each of the durability indexes. In reality the durability indexes may be affected differently by each environmental factor with time, but such data is not available at present.

Despite the limitations as mentioned above, and given the absence of data on particular interactions and the fact that this is a preliminary broad characterisation of the environmental influences, the approach is considered useful.

TABLE 16: HYDRATION RATE WEIGHTING SYSTEM FOR ALL ENVIRONMENTAL FACTORS AND ALL DURABILITY INDEXES

ELEMENT AGE	HYDRATION RATE WEIGHTING FACTORS (%)		
	OPC/GGBS	OPC/FA	OPC/CSF
1 TO 3 DAYS	30	35	60
4 TO 7 DAYS	20	15	20
8 TO 14 DAYS	15	10	10
15 TO 28 DAYS	15	10	5
29 TO 60 DAYS	10	15	1
61 TO 90 DAYS	5	5	1
91 TO 120 DAYS	3	5	2
> 120 DAYS	2	5	1

By applying the scoring and weighting system, as outlined in the two previous sections, it is possible to formulate an environmental scoring for each of the environmental factors i.e. temperature, relative humidity and precipitation, for the individual durability indexes i.e. water sorptivity, oxygen permeability and chloride conductivity. This is outlined below.

4.6 DEVELOPMENT OF THE RATING SYSTEM (STEP 4)

The final step of the environmental characterisation process is to attempt to draw each environmental score for a particular durability index into one single final environmental characterisation factor or rating.

The underlying principle in this step of the procedure is that each environmental factor has a different contribution to the final rating for a particular durability index.

The overall rating is formulated as follows:

- Each durability index is considered separately. The range of percentage variation is extracted from the idealised environmental models for each environmental influence. (Figures 11, 12 and 13);
- For the particular durability index under consideration the ranges of percentage variation per environmental influence are summed; and
- The overall rating is determined by proportioning the variation of the particular environmental factor under consideration to the total summed percentage variation. This is taken to represent the relative influence that a particular environmental factor has on the overall development of the durability index under consideration.

For example, considering water sorptivity, the range of percentage variation per environmental model is as follows: (While it is realised that the various climatic influences will interact, it has been ignored at this stage).

Temperature: (Fig. 11)	51,0% - 23,0% = 28,0%
Relative Humidity: (Fig. 12)	23,0% - 2,0% = 21,0%
Precipitation: (Fig. 13)	23,0% - 1,0% = 22,0%
Total:	Sum = 71,0%

Thus the overall rating for temperature is 28,0% ÷ 71,0% x 100% = 40,0%,
for relative humidity is 30,0% (21,0% ÷ 71,0% x 100%) and
for precipitation is 30,0% (22,0% ÷ 71,0% x 100%).

The implication of this is that, for water sorptivity, temperature has a more important influence on development of sorptivity than either relative humidity or precipitation, the latter two being of equal magnitude. Similar implications can be drawn for the other indexes in relation to the environmental factors.

Table 17 shows the proposed ratings based on the procedure as outlined above.

TABLE 17: RATING SYSTEM FOR EACH ENVIRONMENTAL FACTOR IN RELATION TO THE DURABILITY INDEXES

	WATER SORPTIVITY	OXYGEN PERMEABILITY	CHLORIDE CONDUCTIVITY
TEMPERATURE	40 %	50 %	20 %
HUMIDITY	30 %	10 %	20 %
PRECIPITATION	30 %	40 %	60 %

From the data in Table 17 it is evident that temperature has the largest effect on oxygen permeability, followed by water sorptivity and least effect on chloride conductivity. Conversely relative humidity has the least effect on oxygen permeability and a larger effect on water sorptivity and chloride conductivity. Precipitation has the largest effect on chloride conductivity, followed by oxygen permeability, and least effect on water sorptivity.

4.7 WORKED EXAMPLE

This section sets out a worked example to illustrate the procedure explained in the previous sections of this chapter. For this exercise the chloride conductivity index is selected and the 28-day Overall Environmental Rating is developed based on the effect of relative humidity only. Similar calculations can be done for the other indexes and environmental effects.

4.7.1 PROCEDURE FOR DEVELOPING ENVIRONMENTAL RATING

STEP 1: EVALUATING THE ELEMENT SCORING

Based on the mean relative humidity recorded, a scoring is assigned to the curing achieved on site and the fully water-cured condition, per day. The scoring is assigned based on the relative humidity model for chloride conductivity as explained in Section 4.4. Table 18 shows the mean relative humidity for Wall A at element ages ranging up to 30 days, together with the scoring per day for the site cured and fully water-cured conditions. The element ages are conveniently grouped to facilitate the weighting process as described in Step 2.

STEP 2: APPLYING THE HYDRATION-RATE WEIGHTING

Based on the Hydration Rate Weighting System as set out in Section 4.5 of this chapter, the scoring per age grouping for the site-cured and fully water-cured condition is multiplied to yield the Weighted Scoring. The Weighted Element Score (WES) for the site-cured condition is then compared to the fully water-cured condition and expressed as a percentage attainable scoring. Thus for Wall A (OPC/GGBS Blend) (at 28 days) the relative humidity effect on chloride conductivity is calculated at 86,9% based on the fully water-cured condition, as set out in Table 19.

STEP 3: EVALUATING THE ENVIRONMENTAL RATING

Steps 1 and 2 above are repeated to develop a weighted element score for the Temperature and Precipitation effects. The weighting referred to in this case is to make allowance for curing effect at earlier age as explained in Section 4.6 of this chapter. Table 20 shows the weighted element scores per environmental factor (temperature, relative humidity and precipitation) together with the weighting to develop an overall rating, to characterise the cumulative effect of all the environmental factors on the chloride conductivity of the wall A concrete.

TABLE 18: MEAN RELATIVE HUMIDITY DATA FOR WALL A, AND THE SCORING FOR BOTH SITE-CURED AND FULLY WATER-CURED ELEMENTS.

ELEMENT AGE	MEAN RELATIVE HUMIDITY	ELEMENT SCORING	WET-CURED SCORING	ELEMENT AGE	MEAN RELATIVE HUMIDITY	ELEMENT SCORING	WET-CURED SCORING
1	89	10,0	10,0	15	76	9,5	10,0
2	81	10,0	10,0	16	73	9,1	10,0
3	78	9,7	10,0	17	73	9,1	10,0
	Σ	**29,7**	**30,0**	18	59	6,1	10,0
4	86	10,0	10,0	19	27	0,0	10,0
5	74	9,2	10,0	20	26	0,0	10,0
6	78	9,7	10,0	21	64	7,7	10,0
7	72	8,9	10,0	22	67	8,3	10,0
	Σ	**37,9**	**40,0**	23	79	9,9	10,0
8	78	9,7	10,0	24	61	6,7	10,0
9	95	10,0	10,0	25	59	6,1	10,0
10	83	10,0	10,0	26	92	10,0	10,0
11	86	10,0	10,0	27	87	10,0	10,0
12	83	10,0	10,0	28	69	8,5	10,0
13	83	10,0	10,0	29	72	8,9	10,0
14	80	10,0	10,0	30	74	9,2	10,0
	Σ	**69,7**	**70,0**		Σ	**119,0**	**160,0**

TABLE 19: WEIGHTED ELEMENT SCORING DATA FOR WALL A, FOR BOTH THE SITE-CURED AND FULLY WATER-CURED ELEMENTS.

ELEMENT AGE	WET-CURED SCORING	ELEMENT SCORING	HYDRATION RATE WEIGHTING	WEIGHTED WET-CURED SCORING	WEIGHTED ELEMENT SCORING
1-3	30,0	29,7	30%	9,0	8,9
4-7	40,0	37,9	20%	8,0	7,6
8-14	70,0	69,7	15%	10,5	10,5
15-30	160,0	119,0	15%	24,0	17,8
				51,5	**44,8**
				WES	**86.9%**

The development of the overall weighting is explained in Section 4.2.4 of this chapter and the overall environmental rating is used in this project when evaluating the curing methods. The final overall environmental rating attempts to represent a single ratio of the attainable durability index achieved on-site relative to the fully water cured condition, should no site-curing be applied. In other words the overall rating for wall A of 45,2%, can be interpreted that, given the various environmental exposure conditions imposed on the element during the 28-day period (assuming that no site-curing is applied), a chloride conductivity roughly 45% of that of the fully water cured sample is expected. This, of course, does not take into account the possible effects of various site-curing methods. The data for wall B and C are included as a comparison, having been calculated in the same manner as for wall A.

It must be re-iterated that this model is preliminary and requires refinement when further research data is available. As mentioned previously the limitations of this model are broadly as follows:

- The research data on which the model is based was developed using OPC as a cementitious binder, while in this project blends of OPC with GGBS, FA and CSF were used; and
- The temperature and relative humidity ranges measured on-site fell outside the data envelope used in generating the idealised models.

TABLE 20: FINAL OVERALL ENVIRONMENTAL RATINGS FOR WALL SERIES AT 28 DAYS, BASED ON RESPONSE TO CHLORIDE CONDUCTIVITY.

ELEMENT	TEMPERATURE SCORING	WF	RELATIVE HUMIDITY SCORING	WF	PRECIPITATION SCORING	WF	OVERALL RATING
WALL A	122,5%	20%	87,0%	20%	5,4%	60%	**45,2%**
WALL B	122,2%	20%	79,8%	20%	0,6%	60%	**40,7%**
WALL C	123,8%	20%	84,6%	20%	5,4%	60%	**44,9%**

Notwithstanding these limitations this approach is useful in characterising the effects of the environment on the particular Durability Index under consideration. In fact, an approach of this kind is essential in order to interpret the measured index values on-site, where environmental factors have had an important influence. Without such an approach, much of the site data is meaningless and impossible to interpret.

4.8 DISCUSSION OF ENVIRONMENTAL RATING RESULTS

In this section the final environmental rating is discussed with the primary aim of placing the data in context and evaluating possible trends. To assist with the evaluation the first portion evaluates broadly the environmental rating that can be expected (per durability index) in three areas or regions of South Africa i.e. Cape Town, East London and Johannesburg. The next part reports on the environmental ratings developed for each test element at 28 and 120 days (for each durability index). To place these results in context this section evaluates the environmental rating development with time for the various binders and durability indexes.

4.8.1 EVALUATION OF REGIONAL ENVIRONMENTAL RATING

Based on the scoring system set out in the preceding sections of this chapter and on the weighting system as applied to a OPC/GGBS blend, environmental ratings were calculated for three towns or regions in South Africa i.e. Cape Town, Johannesburg and East London. These regions were selected since they exhibit very different seasonal variations in climate.

Table 21 summarises the seasonal environmental data for the three regions. From the data it is evident that Cape Town is characterised by wet, cold winters with relatively high precipitation and relative humidity. The summer is dry and hot with lower relative humidity. Johannesburg exhibits dry, cold winters with very low relative humidity and precipitation. The relative humidity, although higher in summer, is substantially lower than East London and Cape Town. East London exhibits the most consistent seasonal environmental patterns of the three regions, with very little seasonal variation in environmental factors.

TABLE 21: SEASONAL ENVIRONMENTAL DATA FOR THREE REGIONS SELECTED FOR REGIONAL COMPARISON.

	SPRING	SUMMER	AUTUMN	WINTER	
PRECIPITATION	84mm	49mm	130mm	252mm	CT
TEMPERATURE	8,7°C - 23,5°C	13,2°C - 26,5°C	9,4°C - 25,4°C	7,0°C - 18,1°C	CT
RELATIVE HUMIDITY	71% - 77%	70% - 72%	74% - 81%	79% - 81%	CT
PRECIPITATION	216mm	320mm	158mm	19mm	JHB
TEMPERATURE	9,3°C - 24,2°C	13,9°C - 25,6°C	7,2°C - 18,9°C	4,1°C - 19,4°C	JHB
RELATIVE HUMIDITY	48% - 65%	67% - 71%	57% - 70%	45% - 53%	JHB
PRECIPITATION	292mm	224mm	240mm	165mm	EL
TEMPERATURE	12,0°C - 20,7°C	16,3°C - 25,5°C	12,6°C – 24,8°C	10,3°C - 21,1°C	EL
RELATIVE HUMIDITY	77% - 81%	78% - 82%	73% - 82%	67% - 71%	EL

A ninety-day element age was selected to conveniently span the seasonal cycle. The spring cycle starts in September and ends in November, the summer cycle starts in December and ends in February. The autumn cycle begins in March and ends in May, while the winter cycle begins in June and terminates in August. The environmental data used was mean monthly data as compiled from hourly values in an observation period from 1931 to 1990, as recorded by the South African Weather Bureau[32]. The average humidity and temperature were assumed constant per day for each month, and the average monthly precipitation was spread evenly over each day of the month, to simplify the approach. The precipitation scoring was also simplified in that only a volume component was used (no duration component was applied).

In the figures that follow the environmental rating is plotted on the Y-axis against season on the X-axis for each durability index, for the three regions.

Figure 14 shows the 90-day Environmental Rating for Chloride Conductivity, plotted against the four seasons for OPC/GGBS concretes for the three regions.

4.8.1.1 Discussion

The Chloride Conductivity Index is the least sensitive of the three indexes to environmental variation. This is evident from the relatively consistent environmental ratings as shown in Figure 14. The rating for East London is more constant over the four seasons than the rating for Johannesburg, due to the absence of the climatic extremes that Johannesburg experiences.

The Water Sorptivity Index is the most sensitive of the three indexes to change in relative humidity. Figure 15 is consistent with this in that both East London and Johannesburg exhibit a reduced rating for winter (they both have reduced mean relative humidities during this period). In contrast, Cape Town exhibits a marked increase in rating for winter, which is a period of increased precipitation and relative humidity.

Figure 15 shows the 90-day Environmental Rating for Water Sorptivity, plotted against the four seasons for OPC/GGBS concretes for the three regions.

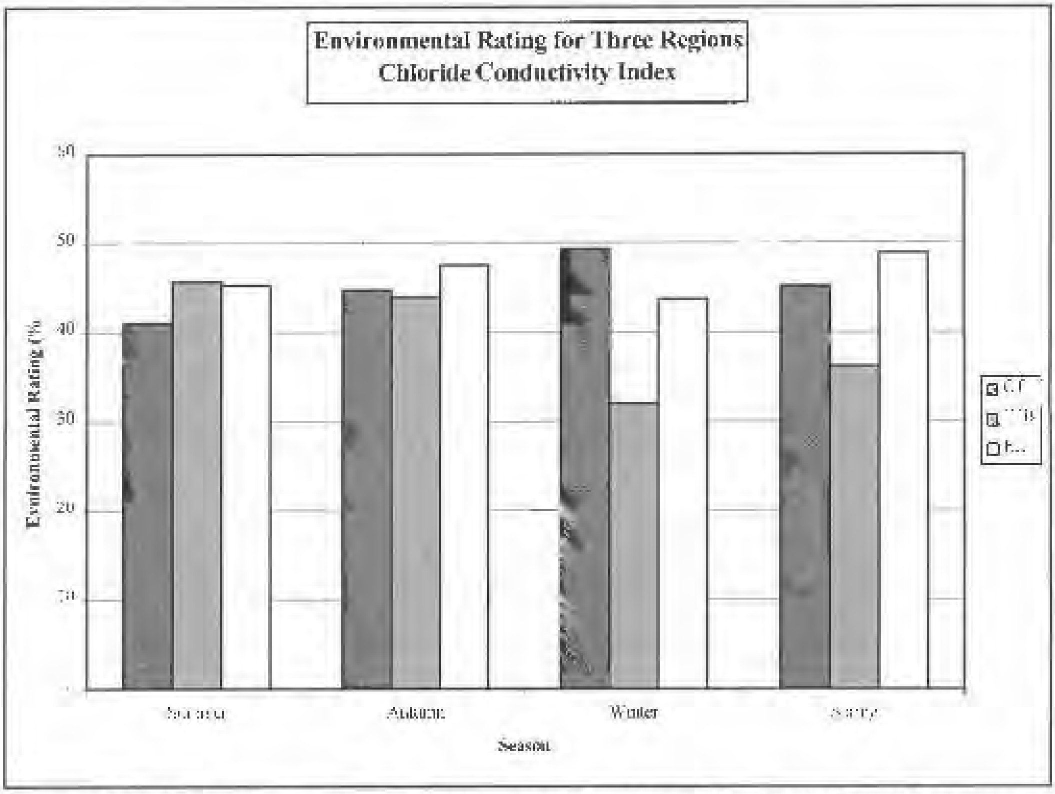


FIGURE 14: ENVIRONMENTAL RATINGS FOR CHLORIDE CONDUCTIVITY PLOTTED AGAINST SEASONS, (OPC/GGBS BINDER).

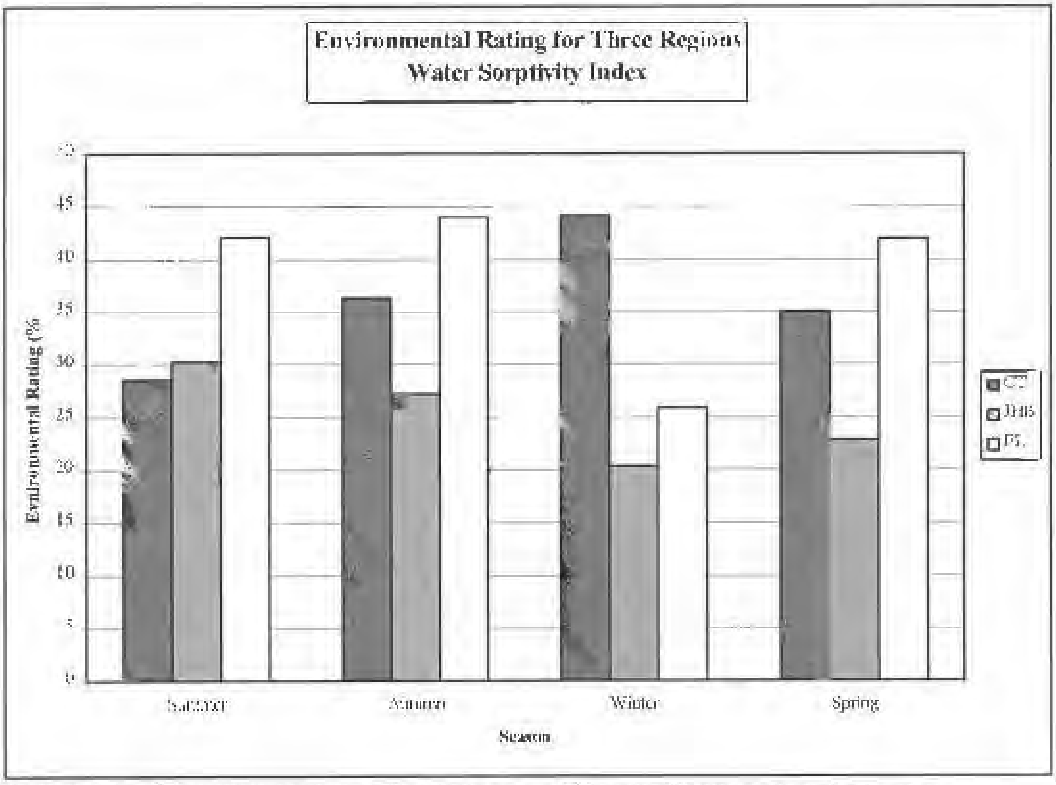


FIGURE 15: ENVIRONMENTAL RATINGS FOR WATER SORPTIVITY PLOTTED AGAINST SEASONS, (OPC/GGBS BINDER).

The oxygen permeability index is the most sensitive of the three indexes to changes in temperature. Figure 16 is consistent with this in that Johannesburg exhibits a substantially reduced rating for winter and spring (a period characterised by low temperatures and low relative humidities). In contrast, Cape Town exhibits a fairly consistent rating for the four seasons. The winter rating for Cape Town is sustained by high relative humidity and precipitation, despite the lower temperature, whereas in spring, temperatures are still fairly low while humidity and precipitation have reduced.

The environmental rating results shown in Figures 14 to 16 indicate that the overall approach, while tentative and limited at this stage, has value. It is able to combine the three important environmental factors (temperature, relative humidity and precipitation) into an overall rating, which also takes account of the different binders used in the concrete. This latter factor cannot be neglected, since the various binders have different rates of hydration. While the evaluation in this section is developed for OPC/GGBS concrete only, the seasonal environmental ratings for OPC/FA and OPC/CSF concretes will vary but follow the same broad trends. The figures also show clearly the difference between a mild, temperate climate such as East London, a temperate climate with much larger extremes such as occurs in Johannesburg, and a climate with cold wet winters and hot dry summers such as occurs in Cape Town. Thus casting concrete in Cape Town in winter would generally provide the best achievable durability indexes, while exactly the opposite applies to Johannesburg. Summer and Autumn would be the most favourable periods for concrete operations in East London.

Figure 16 shows the 90-day Environmental Rating data for oxygen permeability, plotted against the four seasons for OPC/GGBS concretes for the three regions.

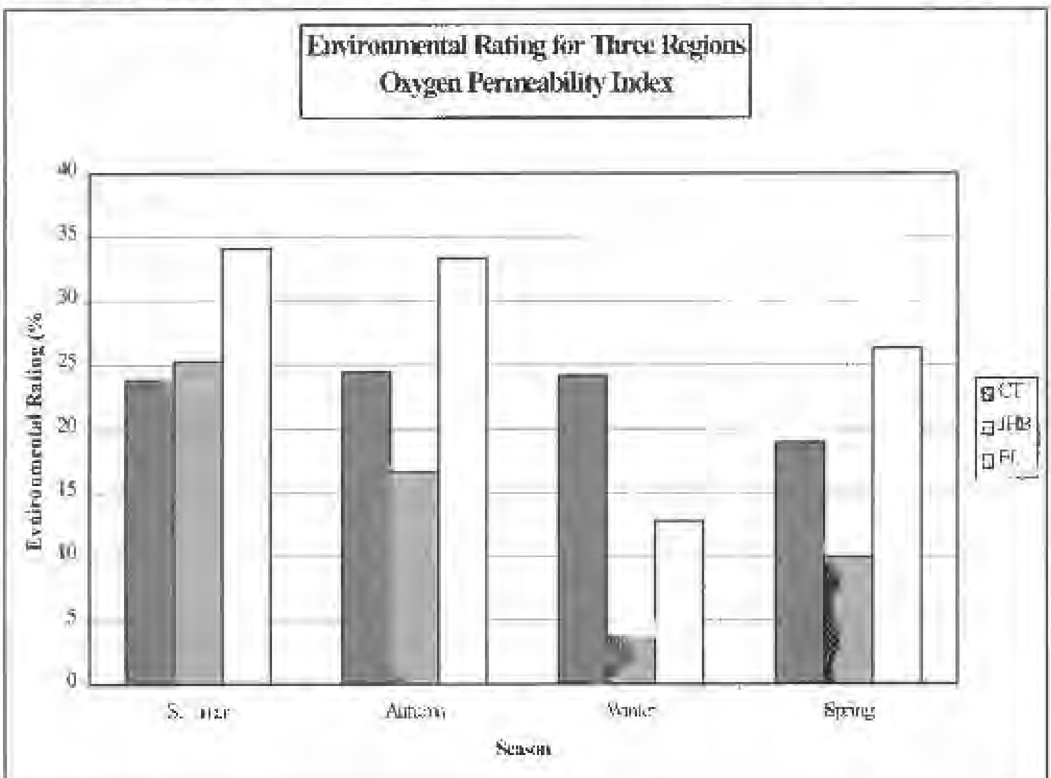


FIGURE 16: ENVIRONMENTAL RATINGS FOR OXYGEN PERMEABILITY PLOTTED AGAINST SEASONS, (OPC/GGBS BINDER).

4.8.1.2 Conclusions

Based on the observations and discussions above the following can be concluded:

- An environment that is characterised by having a high relative humidity, and absence of low temperatures and large fluctuation in environmental conditions is most suited to achieving consistent environmental ratings. The more moderate environment in East London, for example, yields a higher environmental rating than Johannesburg, which experiences greater environmental extremes.

4.8.2 EVALUATION OF ENVIRONMENTAL RATING FOR TEST ELEMENTS

Based on the scoring system set out in the preceding sections of this chapter and on the weighting system as applied to the various binders, the environmental ratings were calculated for the test elements at 28 and 120 days, per durability index. Table 22 summarises the environmental rating for the test elements at 28 and 120 days, per binder type and for each durability index.

4.8.3 DEVELOPMENT OF ENVIRONMENTAL RATING WITH TIME

In order to place the results in Section 4.8.2 in context, and to assist with evaluating the variation between the 28 and 120-day results, the development of the environmental rating with time, per binder type and for each durability index, is examined.

The model is developed for two seasonal cycles, an autumn - winter cycle commencing in May 1997 and ending in August 1997 and a spring - summer cycle commencing in November 1997 and ending in February 1998. The environmental rating development with time terminates at an element age of one hundred and twenty days. The environmental data used was mean monthly data as compiled from hourly values in an observation period from 1931 to 1990, recorded by the South African Weather Bureau[32]. The average humidity and temperature were assumed constant per day for each month, and the average monthly precipitation was spread evenly over each day of the month, to simplify the approach. The precipitation scoring was also simplified in that only a volume component was used (no duration component was applied). Table 24 compares the mean monthly data for East London as measured on-site from April 1997 to March 1998 and the mean data compiled by the South African Weather Bureau[32]. It was decided to use the data as compiled by the South African Weather Bureau[32], since the observation period was longer (compared to the site observations) and thus represented a better reflection of mean values.

TABLE 22: ENVIRONMENTAL RATING TO DURABILITY INDEXES, FOR 28 AND 120-DAY AGES, PER BINDER.

				CHLORIDE CONDUCTIVITY		
28 DAYS	**GGBS**	**SA1**	**SA2**	**SA3**	**SA4**	**WA**
		47,4%	42,8%	45,0%	41,5%	45,2%
	FA	**SB1**	**SB2**	**SB3**	**SB4**	**WB**
		44,2%	43,9%	44,5%	41,3%	40,7%
	CSF	**SC1**	**SC2**	**SC3**	**SC4**	**WC**
		39,7%	44,7%	41,4%	40,5%	44,9%
120 DAYS	**GGBS**	**SA1**	**SA2**	**SA3**	**SA4**	**WA**
		45,7%	43,5%	43,6%	42,4%	44,5%
	FA	**SB1**	**SB2**	**SB3**	**SB4**	**WB**
		43,1%	44,0%	43,2%	42,5%	41,8%
	CSF	**SC1**	**SC2**	**SC3**	**SC4**	**WC**
		40,7%	44,6%	42,1%	41,5%	44,5%
				WATER SORPTIVITY		
28 DAYS	**GGBS**	**SA1**	**SA2**	**SA3**	**SA4**	**WA**
		62,0%	53,6%	59,8%	61,7%	61,5%
	FA	**SB1**	**SB2**	**SB3**	**SB4**	**WB**
		55,1%	56,3%	57,4%	60,5%	55,3%
	CSF	**SC1**	**SC2**	**SC3**	**SC4**	**WC**
		50,7%	55,1%	49,3%	58,0%	54,7%
120 DAYS	**GGBS**	**SA1**	**SA2**	**SA3**	**SA4**	**WA**
		59,0%	57,8%	61,5%	62,9%	58,6%
	FA	**SB1**	**SB2**	**SB3**	**SB4**	**WB**
		56,0%	60,0%	61,7%	62,7%	55,3%
	CSF	**SC1**	**SC2**	**SC3**	**SC4**	**WC**
		53,2%	56,8%	53,5%	60,0%	55,9%
				OXYGEN PERMEABILITY		
28 DAYS	**GGBS**	**SA1**	**SA2**	**SA3**	**SA4**	**WA**
		21,4%	8,4%	25,8%	34,3%	19,1%
	FA	**SB1**	**SB2**	**SB3**	**SB4**	**WB**
		16,3%	8,9%	23,4%	33,9%	15,0%
	CSF	**SC1**	**SC2**	**SC3**	**SC4**	**WC**
		20,5%	8,5%	15,8%	30,6%	14,7%
120 DAYS	**GGBS**	**SA1**	**SA2**	**SA3**	**SA4**	**WA**
		16,9%	12,6%	32,8%	38,2%	15,2%
	FA	**SB1**	**SB2**	**SB3**	**SB4**	**WB**
		14,5%	14,9%	34,0%	38,6%	12,9%
	CSF	**SC1**	**SC2**	**SC3**	**SC4**	**WC**
		19,1%	11,9%	22,4%	32,9%	14,5%

Table 23 details the casting date for each of the test elements and also indicates the separation of the elements into two convenient seasonal cycles i.e. autumn-winter cycle and spring- summer cycle.

TABLE 23: CASTING DATES FOR TEST ELEMENTS, SHOWN SEPARATED INTO TWO SEASONAL CYCLES.

	AUTUMN - WINTER CYCLE (MAY '97 - AUG '97)	**SPRING - SUMMER CYCLE (NOV '97 - FEB '98)**
	CASTING DATE	**CASTING DATE**
WALL A	30 APRIL '97	
SLAB A1	07 MAY '97	
WALL B	13 MAY '97	
SLAB B1	14 MAY '97	
SLAB C1	16 MAY '97	
WALL C	20 MAY '97	
SLAB A2	27 JUNE '97	
SLAB B2	28 JUNE '97	
SLAB C2	29 JUNE '97	
SLAB A3		15 NOV '97
SLAB B3		16 NOV '97
SLAB C3		17 NOV '97
SLAB A4		12 DEC '97
SLAB B4		13 DEC '97
SLAB C4		15 DEC '97

TABLE 24: MEAN ENVIRONMENTAL DATA (RELATIVE HUMIDITY, PRECIPITATION AND TEMPERATURE) MEASURED ON-SITE, COMPARED WITH MEAN DATA AS SUPPLIED BY SOUTH AFRICAN WEATHER BUREAU[32], BASED ON A 60 YEAR RECORD.

	MEAS. RH (%)	**MEAN RH (%) SA WB**	**MEAS. PREC. (mm)**	**MEAN PREC. (mm) SAWB**	**MEAS. TEMP. (°C)**	**MEAN TEMP. (°C) SAWB**
APRIL '97	82	78	196	83	20,1	20,4
MAY '97	73	73	111	52	17,6	17,6
JUNE '97	69	67	181	40	15,7	15,9
JULY '97	71	68	18	47	14,9	15,6
AUG '97	77	71	31	78	16,1	15,6
SEPT '97	78	78	9	80	17,1	16,3
OCT '97	74	77	73	102	18,5	17,0
NOV '97	74	81	120	110	18,9	18,2
DEC '97	78	78	4	63	20,6	20,3
JAN '98	77	81	58	69	21,7	21,6
FEB '98	82	82	44	92	22,9	21,7
MAR '98	82	82	189	105	21,2	20,9

Figures 17 to 19 show the environmental rating development with time, for chloride conductivity, water sorptivity and oxygen permeability for each binder type. The environmental rating is plotted on the Y-axis against age on the X-axis for each durability index, for the binder types.

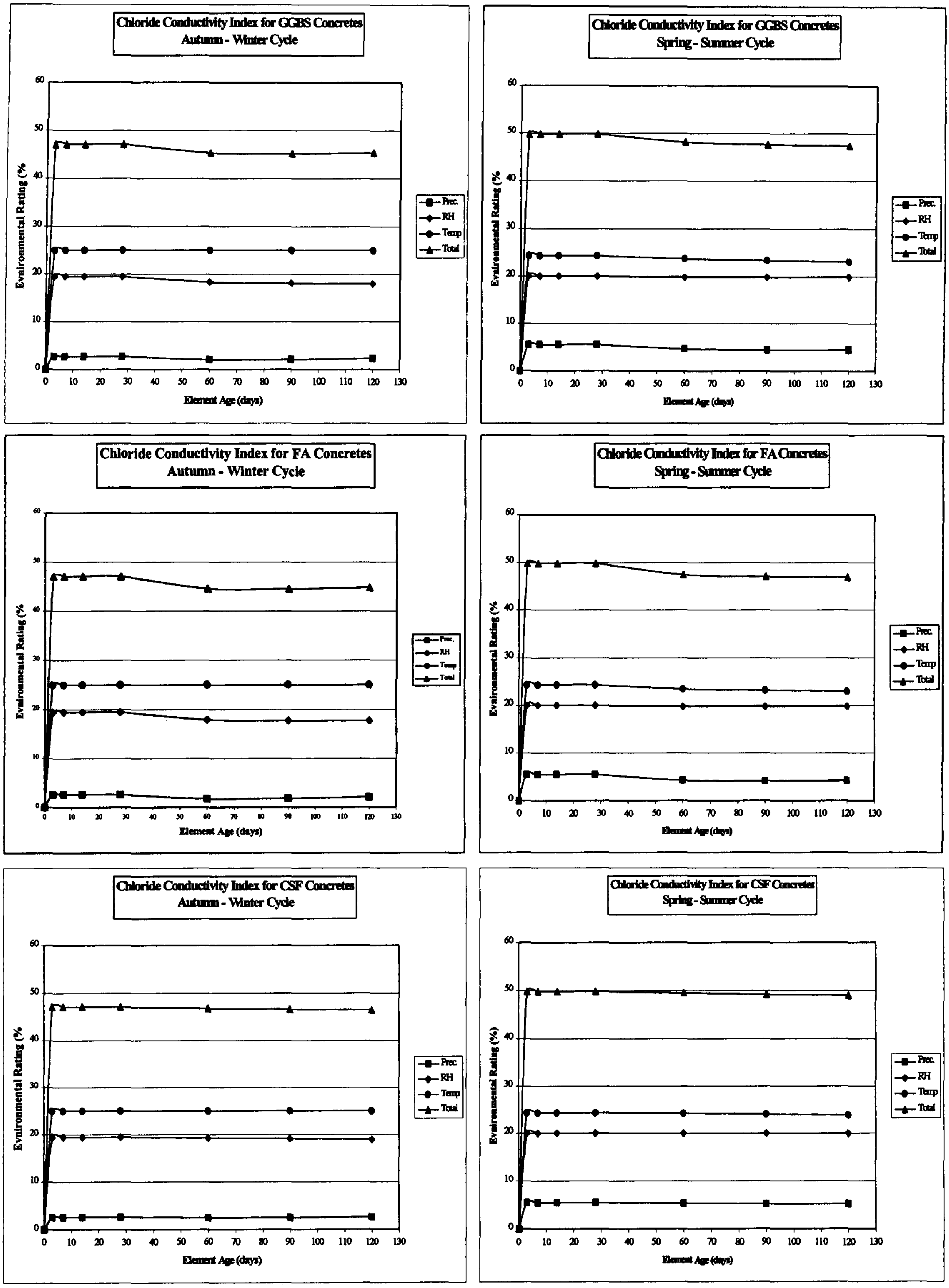


FIGURE 17: ENVIRONMENTAL RATINGS DEVELOPMENT WITH TIME FOR CHLORIDE CONDUCTIVITY, FOR TWO SEASONAL CYCLES, (ALL CONCRETES).

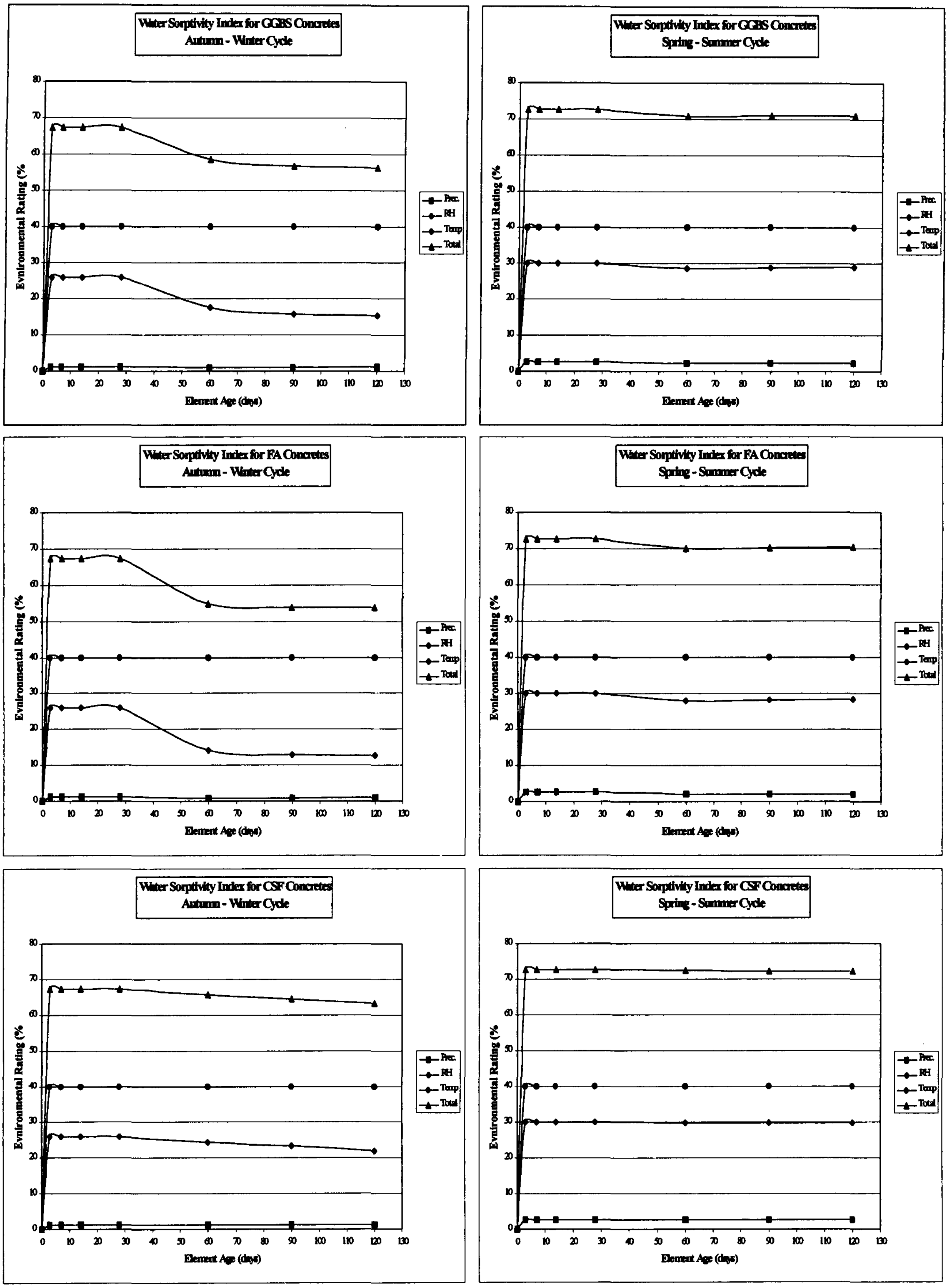


FIGURE 18: ENVIRONMENTAL RATINGS DEVELOPMENT WITH TIME FOR WATER SORPTIVITY, FOR TWO SEASONAL CYCLES, (ALL CONCRETES).

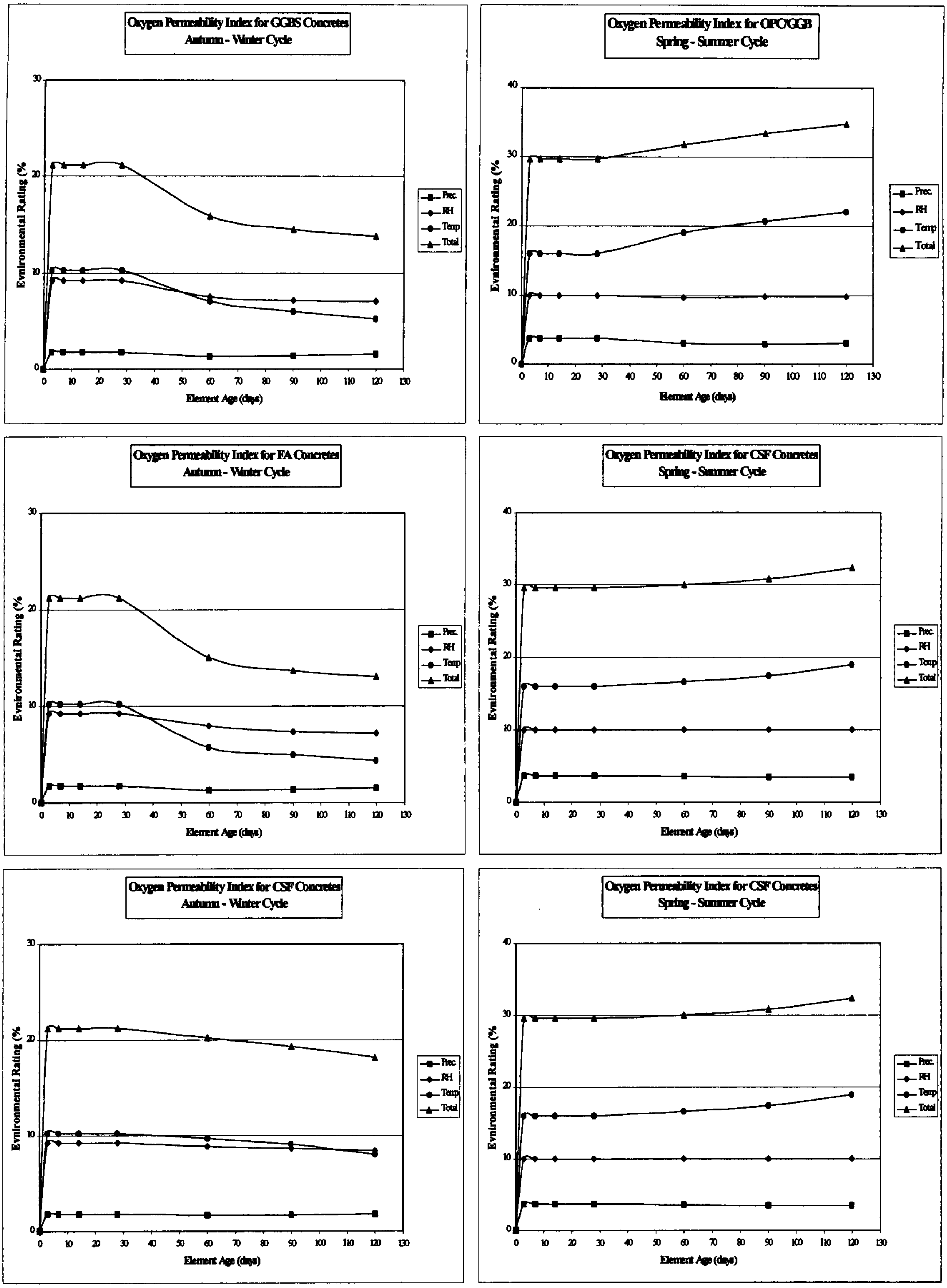


FIGURE 19: ENVIRONMENTAL RATINGS DEVELOPMENT WITH TIME FOR OXYGEN PERMEABILITY INDEX, FOR TWO SEASONAL CYCLES, (ALL CONCRETES).

4.8.3.1 Discussion

4.8.3.1.1 General

For both cycles the environmental rating develops largely within the first three days of casting. The changes from that point forward are generally small in relation to the early age increase in environmental rating. This reinforces the crucial nature of the early age curing history of the concrete, indicating that essentially it is in this period that the durability properties will be developed.

4.8.3.2 Chloride Conductivity

4.8.3.2.1 Autumn-Winter Cycle

Precipitation yielded the lowest contribution to the total environmental rating for all binder types (3%) and remained unchanged with time. The contribution of relative humidity at 28 days is 20% for all the binders, and reduces to 17% at 120 days for GGBS and FA concretes and 19% for CSF concretes. The decrease in contribution made by the relative humidity is due to the reduction in relative humidity with the onset of winter in East London. This reduction is more evident for the GGBS and FA concretes than the CSF concretes due to the hydration rate weighting. The contribution made by temperature is consistent at 25% for both 28 days and 120 days for all the concrete types. The reason for this is that the temperature remains below 18°C and thus effects a maximum scoring in terms of chloride conductivity (refer Section 4.4).

The total environmental rating reduces from 47% at 28 days to 45% at 120 days, for GGBS and FA concretes and from 50% at 28 days to 48% at 120 days for CSF concretes. By comparison the environmental ratings for the test elements range from 42,8% to 47,4% at 28 days and 43,5% to 45,7% at 120 days for GGBS concretes; from 40,7% to 44,2% at 28 days and 41,8% to 44,0% at 120 days for FA concretes; and from 39,7% to 44,9% at 28 days and 40,7% to 44,6% at 120 days for CSF concretes. This represents a very good correlation with the results as presented in Figure 16.

4.8.3.2.2 Spring-Summer Cycle

Precipitation yielded the lowest contribution to the total environmental rating for all binder types (5%) and remained unchanged with time. The increase in the contribution when compared to the autumn-winter cycle is due to the increase in precipitation in the spring-summer cycle.

The contribution of relative humidity is consistent at 20% for both 28 days and 120 days for all the binder types. The reason for this is that the relative humidity remains above 80% for the spring-summer cycle and thus effects a maximum scoring in terms of chloride conductivity. The contribution made by temperature reduces slightly from 25% at 28 days, to 23% at 120 days for all the binder types. The reason for this is that the temperature increases with the onset of summer in East London, thus reducing the scoring for chloride conductivity.

The total environmental rating reduces from 50% at 28 days to 47% at 120 days, for GGBS and FA concretes. For CSF concretes the total environmental rating reduces from 50% at 28 days to 49% at 120 days. By comparison the environmental ratings for the test elements range from 41,5% to 45,0% at 28 days and 42,4% to 43,6% at 120 days for GGBS concretes; from 41,3% to 44,5% at 28 days and 42,5% to 42,2% at 120 days for FA concretes and from 40,5% to 41,4% at 28 days and 41,5% to 42,1% at 120 days for CSF concretes. This represents a reasonable correlation with the results presented in Figure 16, but the element ratings are lower than the results presented in the figure. The mean monthly relative humidity measured on-site in November 1997 was 74%, while 81% was used in developing the rating duration model (obtained from the South African Weather Bureau[32]). This accounts for the lower environmental ratings obtained by the test elements over this cycle. It must also be noted that the element ratings are calculated on recorded daily mean data (not monthly means) which also can influence the environmental rating, particularly if large variations in environmental factors occur in the first three days after casting.

4.8.3.3 Water Sorptivity

4.8.3.3.1 Autumn-Winter Cycle

Precipitation yielded the lowest contribution to the total environmental rating for all concrete types (2%) and remained unchanged with time. The contribution of relative humidity at 28 days is 26% for all the concretes, and reduces to 16% at 120 days for GGBS concretes, 13% for FA concretes and 22% for CSF concretes. The decrease in contribution made by the relative humidity is due to the reduction in relative humidity with the onset of winter in East London. This reduction is more evident for the GGBS and FA concretes than the CSF concretes due to the hydration rate weighting. The contribution made by temperature is consistent at 40% for both 28 days and 120 days for all the concrete types. The reason for this is that the temperature remains below 18°C and thus effects a maximum scoring for water sorptivity (refer Section 4.4).

The total environmental rating reduces from 68% at 28 days for all concretes to 58% at 120 days for GGBS concretes, 53% for FA concretes and 63% for CSF concretes. By comparison the environmental ratings for the test elements range from 53,6% to 62,0% at 28 days and 57,8% to 59,0% at 120 days for GGBS concretes; from 55,1% to 56,3% at 28 days and 55,3% to 60,0% at 120 days for FA concretes and from 50,7% to 55,1% at 28 days and 53,2% to 56,8% at 120 days for CSF concretes. At 28 days the correlation between the test element environmental rating and the rating development model is poor. This is contrary to what is anticipated considering that the mean relative humidity measured on-site is larger than the results used to develop the model. Considering that the test element ratings are calculated on measured daily mean environmental rating results (not monthly means), this is plausibly the cause of the large variation noted. For the first seven days after casting the measured daily mean relative humidity ranges from 26% to 79% for Slab C1 (rating of 50,7% at 28 days), while the monthly mean is 73% (May 1997). Thus large variations in relative humidity within the early age curing history of test element, results in reduced environmental rating as noted here. At 120 days the correlation is better due to the lesser weighting in terms of hydration rate.

4.8.3.3.2 Spring-Summer Cycle

Precipitation yielded the lowest contribution to the total environmental rating for all concrete types (4%) and remained unchanged with time. The increase in the contribution when compared to the autumn-winter cycle is due to the increase in precipitation in the spring-summer cycle in East London.

The contribution of relative humidity is consistent at 20% for both 28 days and 120 days for all the concrete types. The reason for this is that the relative humidity remains above 80% for the spring-summer cycle and thus effects a maximum scoring for water sorptivity. As for relative humidity the contribution made by temperature remains constant with age at 40%, for the same reason. The total environmental rating remains constant at 72% at 28 days and 120 days, for all the concretes. By comparison the environmental ratings for the test elements range from 59,8% to 61,7% at 28 days and 61,5% to 62,9% at 120 days for GGBS concretes; from 57,4% to 60,5% at 28 days and 61,5% to 62,9% at 120 days for FA concretes and from 49,3% to 58,0% at 28 days and 53,5% to 60,0% at 120 days for CSF concretes. As for the autumn-winter cycle the poor correlation noted here (between the rating for the test elements and the rating development model), is due to changes in relative humidity within the early age curing history. The mean daily relative humidity for Slab 3 (rating of 49,3% at 28 days) ranged from 49% to 73% in the first seven days after casting, while the mean monthly relative humidity is 81% (November 1997).

4.8.3.4 Oxygen Permeability Index

4.8.3.4.1 Autumn-Winter Cycle

Precipitation yielded the lowest contribution to the total environmental rating for all concretes types (2%) and remained unchanged with time. The contribution of relative humidity at 28 days is 9% for all the binders, and reduces to 7% at 120 days for GGBS and FA concretes and 8% for CSF concretes. The decrease in contribution made by the relative humidity is due to the reduction in relative humidity with the onset of winter. This reduction is more evident for the GGBS and FA concretes than the CSF concretes due to the hydration rate weighting. The contribution made by temperature reduces from 10% at 28 days (for all the binders) to 5% at 120 days for GGBS and FA concretes and 8% for CSF concretes at 120 days.

The total environmental rating reduces from 22% at 28 days for all the concretes to 14% for GGBS concretes and FA concretes and 18% for CSF concretes at 120 days. By comparison the environmental ratings for the test elements range from 8,4% to 21,4% at 28 days and 12,6% to 16,9% at 120 days for GGBS concretes; from 8,9% to 16,3% at 28 days and 12,9% to 14,9% at 120 days for FA concretes; and from 8,5% to 20,5% at 28 days and 11,9% to 19,1% at 120 days for CSF concretes. At 28 days the correlation between the test element environmental rating and the rating development model is poor. This is largely due to the lower limit of the range i.e. 8,4% (GGBS - SA2), 8,9% (FA - SB2) and 8,5% (CSF - SC2). The upper limit of the results correlates very well with the rating development model. In the first seven days after casting the measured daily mean temperature ranges from 10,6°C to 14,2°C (Slab C2), 10,6°C to 15,0°C (Slab B2) and 10,6°C to 17,4°C (Slab A2). These temperature ranges are substantially lower than those measured for the other test elements and this is anticipated given that they were cast towards the end of June 1997. This yields the low environmental ratings evident for the test elements. At 120 days the correlation is better due to the lesser weighting in terms of hydration rate.

4.8.3.4.2 Spring-Summer Cycle

Precipitation yielded the lowest contribution (3%) to the total environmental rating for all concrete types and remained unchanged with age. The increase in the contribution when compared to the autumn-winter cycle is due to the increase in precipitation in the spring-summer cycle. The contribution of relative humidity is consistent at 10% for both 28 days and 120 days for all the binder types. The reason for this is that the relative humidity remains above 80% for the spring-summer cycle and thus effects a maximum scoring in terms of oxygen permeability. The contribution of temperature increases from 16% at 28 days (for all the binders) to 22% at 120 days for GGBS concretes and FA concretes and 19% for CSF concretes at 120 days. The increase in the contribution made by temperature is due to the increase in temperature with the onset of summer in East London, the sensitivity of oxygen permeability scoring to temperature and the variation between binders is due to the hydration rate weighting.

The total environmental rating increases from 30% at 28 days for all the concretes to 35% for GGBS and FA concretes and 32% for CSF concretes at 120 days. By comparison the environmental ratings for the test elements range from 25,8% to 34,3% at 28 days and 32,8% to 38,2% at 120 days for GGBS concretes; from 23,4% to 33,9% at 28 days and 34,0% to 38,6% at 120 days for FA concretes; and from 15,8% to 30,6% at 28 days and 22,4% to 32,9% at 120 days for CSF concretes. While the value of the environmental rating varies considerably and does not correlate very well with the rating development model, the same trends are evident i.e. the increase in rating with element age. The reason for the large variation in environmental rating for the test elements is due to the changes in mean daily temperature measured on-site.

4.9 CONCLUSIONS

Based on the observations and discussions above the following can be concluded:

- Considering the data for environmental rating for the test elements, the assumptions made in developing the characterisation system appear to be validated by the regional results. Notwithstanding this a substantial amount of work is still required to refine the system; and
- When considering the durability indexes presented in subsequent chapters it must be noted that in a regional context East London (hence the test elements) has an environment favourable to the development of superior durability. By contrast, had this study been undertaken in Johannesburg it would be expected that in winter and spring substantially lower ratings would have been achieved. In other words with the same curing effort poorer durability properties would have been realised.

GENERAL PREFACE TO CHAPTERS 5, 6 & 7

1. INTRODUCTION

This section outlines the general structure and objectives of chapters 5, 6 and 7. The main objectives of the project are also briefly restated.

The primary objective of the project was to measure the durability indexes (chloride conductivity, water sorptivity and oxygen permeability) in typical site conditions and to attempt to establish the effect of two "primary variables" (i.e. binder type and curing method). The ultimate aim is to expand our understanding on how to achieve durable concrete by intelligent use of both binder type and curing methodology.

The influence of four further variables were also analysed, namely, water/binder ratio, change in cement manufacture specification, climatic/environmental effects, and element age. These are considered to be "secondary variables". This term does not indicate that these variables are of lesser importance than the "primary variables", but that they were ancillary to the primary objective of determining the effects of binder type and curing method on the durability. These "secondary variables" are briefly discussed below.

At the outset, the aim of the project was to produce a series of test elements using three binder types within a narrow window of compressive strength. Due to the varied strength performance of the binder types, the water/binder ratio was not constant for all test elements.

Two series of test elements were cast (walls and slabs) for each binder type, with different design compressive strengths for the two elements at 28 days. Given the different design compressive strength this also resulted in different water/binder ratios between the various test elements of the same binder type. In other words the wall series had a particular water/binder ratio and the slabs a different one, which varied for the binder type used. For the wall series only one test element was cast, while for the slabs four elements were cast (the number of test elements cast matches the casting duration of the modelled structures). This means that given the information available only a limited evaluation with respect to water/binder ratio is possible.

During the casting of the test elements the specification governing the manufacture of Ordinary Portland Cement changed in South Africa. This resulted in the walls and slab 1 and 2 series being cast using "OPC" (manufactured in accordance with the "old" specification), while slab 3 and 4 series were cast using "CEM I 42,5" (manufactured in accordance with the newly adopted specification.) This could have had an influence on the parameters measured and must be considered in the analysis of the data.

Due to the location of the test elements they were exposed to variations in temperature, humidity and precipitation. With the limited information presently available on how environmental conditions affect the durability indexes, the approach adopted is to prepare a "preliminary" environmental characterisation system. The system was described in detail in chapter 4, and attempts to quantify the relative effect of the environment across the full range of test elements.

At the outset of the project the age for coring the samples was set at 28 days. After scrutinising the first batch of results it was decided to repeat coring at 120 days, to assist with the evaluation of various trends and anomalies. This has resulted in two sets of data, which can be used to evaluate the change of particular parameters with element age.

The chapters begin by focusing briefly on the effects of water/binder ratio on the durability of fully cured elements. Next, the effect of the binder type and element age on the durability index is evaluated using the results from the "best controlled" tests - i.e. the fully cured cubes. By using these results it is possible to limit the variables and formulate an understanding of how these three variables affect the index under consideration.

The last section of the chapters focuses on the curing method and how this affects the durability indexes. This is the variable that has been tested under uncontrolled "site conditions" and accordingly the results must be evaluated within the broad framework of the environmental classification system, in an attempt to understand how the various curing methods affect the respective durability indexes.

In the evaluation of all the above variables the change in cement specification is constantly considered, in that grouping of the related elements is discussed.

2. WATER/BINDER RATIO

In the chapters the link between water/binder ratio and the respective durability index is explored. The primary aim is to attempt to establish the degree to which, in this work, the water/binder ratio had an effect on durability indexes. Since information is available for three cement extender types it may be possible to comment briefly on the relative sensitivity of the extender type to variation of water/binder ratio.

The results used for comparative purposes were derived from specimens cored from cubes (made at the time of casting the test element) and cured in a temperature-controlled curing bath for the full duration period to coring at 28 or 120 days.

The following further variables were included in the evaluation:

- Binder Blend Type;
- Cement Manufacture Specification; and
- Element Age.

The following approach is adopted in the subsequent chapters in an attempt to present the data graphically, conducive to evaluation of broad trends:

The dependant variable (the durability index under consideration) is plotted on the Y-axis against water/binder ratio (the independent variable) on the X-axis.

Using a legend, the variation in binder blend type and cement manufacture specification is included on a single figure. The 28 and 120-day results are depicted on separate figures.

3. BINDER TYPE

The link between binder type and the durability index is explored in the subsequent chapters. The primary aim was also to attempt to establish which binder had the most beneficial effect on durability index, in the sense of improving the potential durability of the elements.

The results used for comparative purposes are derived from specimens cored from cubes (made at the time of casting the test element) and cured in a temperature-controlled curing bath for the full period prior to coring at 28 or 120 days.

The effects of the following further variables are also included:

- Binder Blend Type;
- Element Age; and
- Cement Manufacture Specification.

The following approach is adopted in the subsequent chapters in an attempt to present the data graphically, conducive to evaluation of broad trends:

The dependant variable (the durability index under consideration) is plotted on the Y-axis against core compressive strength on the X-axis. Core compressive strength is not a true independent variable, however it was selected given its suitability as a common base. Using a legend accommodates the variation in binder type and change in cement manufacture specification on a single figure. The element ages are considered separately at 28 and 120 days.

4. ELEMENT AGE

The link between element age and the respective durability index is explored. The primary aim is to attempt to establish the degree to which the durability indexes change with time. The secondary aim is to attempt to establish possible trends with respect to change in durability index.

The results used for comparative purposes are derived from samples cored from cubes (made at the time of casting the test element) and cured in temperature-controlled curing bath for the full period prior to coring at 28 or 120 days.

The effects of the following further variables are also included:

- Binder Blend Type; and
- Cement Manufacture Specification.

The following approach is adopted in the subsequent chapters in order to present the data graphically, conducive to evaluation of broad trends:

The dependant variable (the durability index under consideration) is plotted on the Y-axis against core compressive strength on the X-axis. A legend accommodates the variation in element age and change in cement manufacture specification on a single figure. The binder blend types (GGBS, FA and CSF) are considered separately. A "trendline" is added to indicate broadly the change in durability index with time.

5 CURING METHOD

In this section the link between curing method and durability index is explored. The primary aim is to attempt to establish, for each binder type how the particular durability index is affected by curing, and which curing method has the most beneficial effect.

The results used for comparative purposes were extracted from cores from the various test elements at 28 days or 120 days.

The following variables are included:

- Binder Type;
- Curing Method;
- Environmental Conditions – Variation of Temperature, Relative Humidity and Precipitation;
- Element Age;
- Test Element – Walls or Slabs; and
- Cement Manufacture Specification.

The following approach is adopted to present the data graphically:

The dependant variable (the durability index under consideration) is plotted on the Y-axis against curing method on the X-axis, with the environmental rating reported. The environmental rating relates the various site-cured conditions to the fully water-cured condition at the respective element ages. Chapter 4 explains the procedure to develop the environmental rating for each specific element.

By separating Wall and Slab elements it is possible to consider the effect of element orientation (i.e. vertical or horizontal). It is not possible in this case to consider Wall and Slab elements in a single evaluation, given their different compressive strengths. The various binder types are shown on a single figure and the element ages are considered separately (28 days and 120 days).

The change in cement manufacture specification is only evident when considering the Slab series, since all the Wall series were cast using cement manufactured under the same specification (i.e. OPC).

The 28-day data is evaluated first since it is reasoned that the possible masking effect of the environment will be less pronounced at the earlier age than at 120 days. The environmental rating system evaluates the environmental conditions as would be experienced in an "unshielded" or fully exposed environment. No cognisance is taken of the possible effect the curing method may have had on the environmental rating. It is certain that the use of a layer of sand (for example) *will have some insulating effect on the surface of the concrete. In an attempt to take the effect of the different curing methods, into account, the evaluation begins by considering the uncured condition since this is a condition truly exposed to the environment. The various curing methods will obviously have "masked" the actual environmental conditions on the concrete elements. Therefore comparing the results for the various curing methods with the uncured condition will immediately highlight the effectiveness of the curing methods.*

6 OXYGEN PERMEABILITY

Given that the Oxygen Permeability Index (OPI) is the negative log of the Darcy coefficient of permeability (k), the larger the Oxygen Permeability Index the smaller k and thus the more favourable the durability properties realised. This is in direct contrast with the chloride conductivity and water sorptivity where the smaller the result the more favourable the durability properties. In an attempt to remain consistent the Y-axis of all figures showing OPI results are inverted i.e. decreasing in value away from the X-axis. In chapter 7 reference is made to both the Oxygen Permeability and the Oxygen Permeability Index. The term Oxygen Permeability refers to the Darcy coefficient of permeability (k) and Oxygen Permeability Index to the negative log of k. Any evaluation of change in Oxygen Permeability Index results is based on k as also the curing reduction ratio and this is suitably noted at the location.

CHAPTER 5

CHLORIDE CONDUCTIVITY RESULTS

5.1 INFLUENCE OF WATER/BINDER RATIO

5.1.1 CHLORIDE CONDUCTIVITY RESULTS AT 28 DAYS

Table 25 shows the water/binder ratios that were used to achieve a characteristic compressive strength of 30 MPa for the wall series and 35 MPa for the slab series, for the three concrete types.

TABLE 25: WATER/BINDER RATIOS FOR WALL AND SLAB ELEMENTS.

BINDER TYPE	WATER/BINDER RATIO	
	WALL SERIES	SLAB SERIES
CEMENT/GGBS	0,50	0,46
CEMENT/FA	0,50	0,47
CEMENT/CSF	0,57	0,54

Figure 20 shows the chloride conductivity results for 28-day wet-cured cubes plotted against the respective water/binder ratio, for the three binder types.

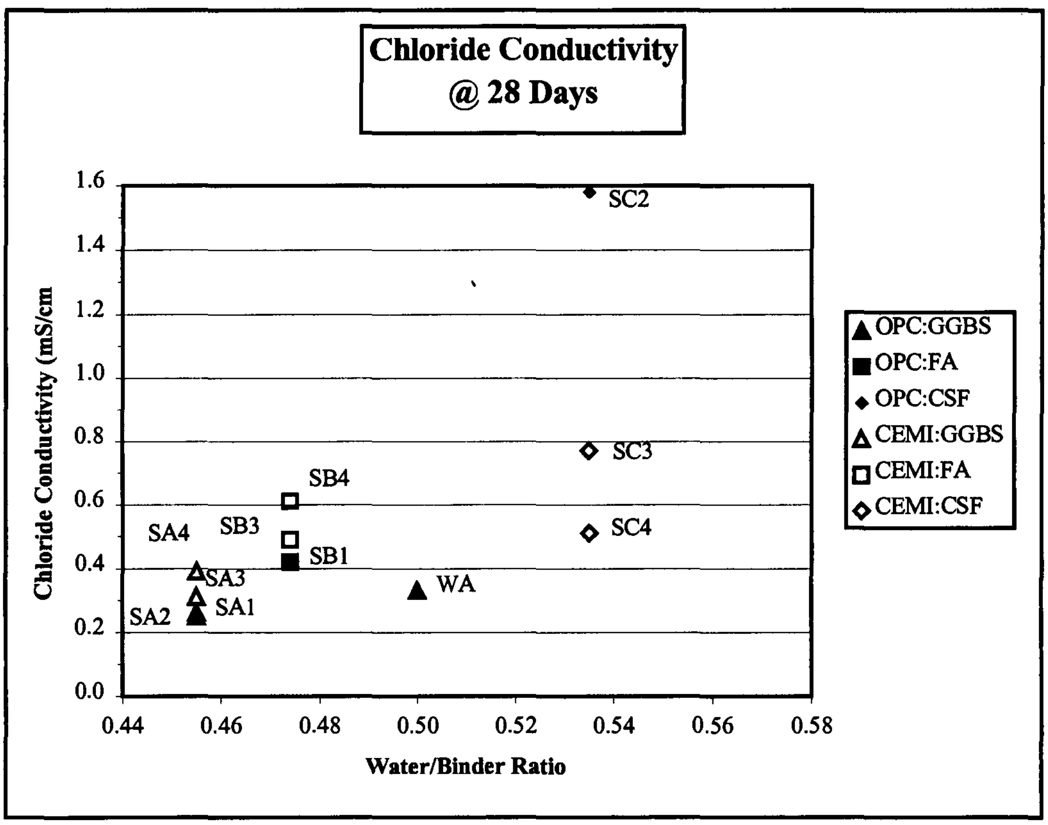


FIGURE 20: CHLORIDE CONDUCTIVITY RESULTS FOR 28-DAY WET-CURED CUBES, PLOTTED AGAINST WATER/BINDER RATIO.

For the GGBS concretes, a group of results related to the change in cement manufacture specification is evident. Slab 3&4 series (based on CEM I cement) are grouped together and so too are slab 1&2 series (based on OPC cement). The shift is of the order of 0,20 mS/cm and it appears that OPC cement has the effect of marginally reducing (i.e. improving) the chloride conductivity. Given the absence of a result for slab B2, it is not possible to comment on this trend regarding the FA concrete, however it appears feasible that it is repeated, since the result for slab B1 is lower than for slab B3&4. A similar situation exists regarding the CSF concrete making it difficult to comment decisively on the effect of cement type.

For the slab series the OPC/GGBS concrete yields the lowest chloride conductivity results in the range 0,25 mS/cm to 0,26 mS/cm. The OPC/FA concrete results are larger (poorer properties), than the OPC/GGBS concrete of the order of 0,42 mS/cm. The OPC/CSF result (1,58 mS/cm) is considerably higher (poorer properties) than the OPC/GGBS and OPC/FA concretes.

For the slab series the CEM I/GGBS concrete yields chloride conductivity results in the range of 0,31 mS/cm to 0,39 mS/cm. The CEM I/FA concrete yields results in the range of 0,49 mS/cm to 0,61 mS/cm and the CEM I/CSF concrete yields chloride conductivity results in the range of 0,51 mS/cm to 0,77 mS/cm. The CEM I/GGBS concrete yields the lowest chloride conductivity while the result for the CEM I/FA concrete is noticeably larger (poorer properties), followed by the CEM I/CSF results. Interestingly the variation between the individual results is larger for CEM I concretes.

For the wall series the OPC/GGBS concrete yield a chloride conductivity of 0,33 mS/cm. (No data is available for either the GGBS or FA concretes for the wall series).

As a general characterisation[33], chloride conductivity below 0,75 mS/cm is considered to provide "Excellent" durability properties, above 0,75 mS/cm and below 1,5 mS/cm is considered "Good" and above 1,5 mS/cm is considered "Poor". All of the results for GGBS and FA concretes satisfy or exceed the "Excellent" durability category. For the CSF concretes the results vary from "Excellent" to "Poor".

Ignoring the results for samples cast using CEM I cement and broadly comparing the results for slabs and walls cast using OPC cement (only possible for OPC/GGBS), it is noted that as the water/binder ratio decreases (the quantity of binder increases) the chloride conductivity reduces (i.e. improved properties).

When comparing the above data with currently available chloride conductivity data, from the Western Cape[18], for 28-day wet-cured samples, it was noted that the GGBS concretes exhibited similar results. The FA concrete results, for this project, were however noticeably lower (of the order of three times) and the CSF concrete results, for this project, were somewhat poorer (of the order of three times). This variation confirms the influence of the material (course and fine aggregate) selection on the chloride conductivity developed.

5.1.2 CHLORIDE CONDUCTIVITY RESULTS AT 120 DAYS

Figure 21 shows the chloride conductivity results for 120-day wet-cured cubes plotted against the respective water/binder ratio, for the three concrete types.

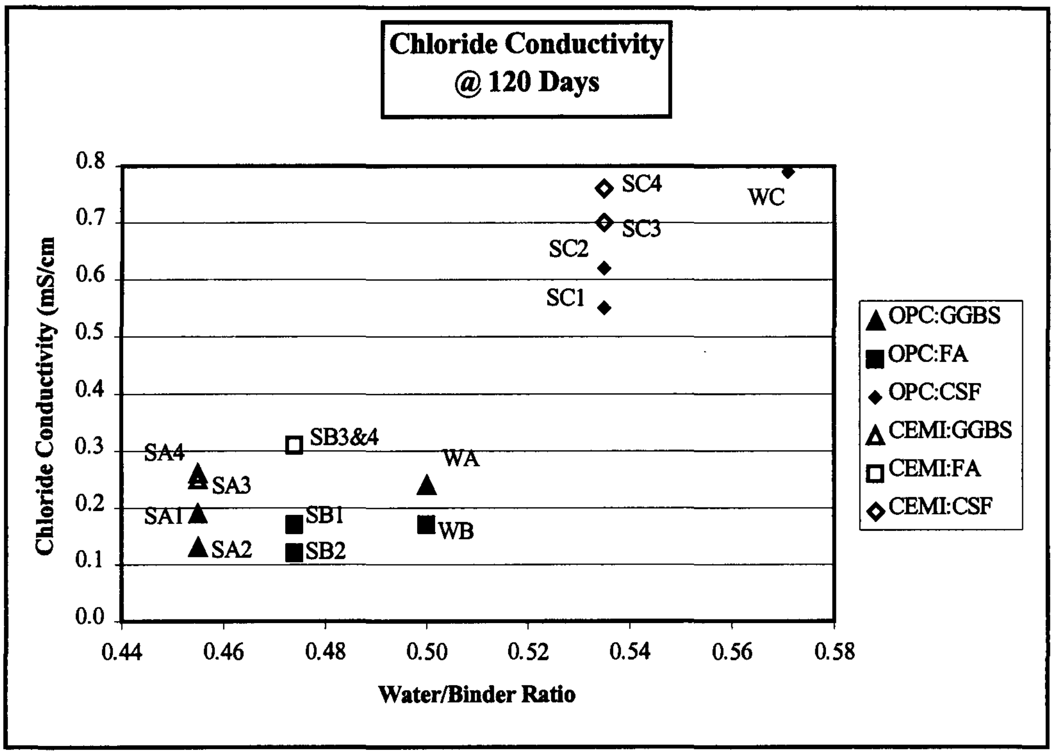


FIGURE 21: CHLORIDE CONDUCTIVITY RESULTS FOR 120-DAY WET-CURED CUBES, PLOTTED AGAINST WATER/BINDER RATIO.

For all three the concrete types, a group of results related to the change in cement manufacture specification is evident, with a distinct grouping of the slab 3&4 series and slab 1&2 series. The shift is of the order of 0,20 mS/cm and the OPC cement has the effect of marginally reducing (i.e. improving) the chloride conductivity. It appears that the FA concretes exhibit the most sensitivity to the change in cement manufacture specification (exhibit the largest shift between the grouping of results).

For the slab series the OPC/GGBS concrete yields chloride conductivity results in the range of 0,13 mS/cm to 0,19 mS/cm at 120 days. The OPC/FA concrete yields results in the range of 0,11 mS/cm to 0,17 mS/cm and OPC/CSF concrete in the range of 0,55 mS/cm to 0,62 mS/cm. The OPC/GGBS and OPC/FA concretes yield the lowest chloride conductivity while the result for the OPC/CSF concretes are noticeably larger (poorer properties).

For the slab series the CEM I/GGBS concrete yield chloride conductivity results in the range of 0,25 mS/cm to 0,26 mS/cm. The CEM I/FA concrete yield a result of 0,31 mS/cm and CEM I/CSF concrete yields results in the range of 0,70 mS/cm to 0,76 mS/cm. The CEM I/GGBS and CEM I/FA concretes yields the lowest chloride conductivity while the result for the CEM I/CSF concrete is noticeably larger (poorer properties. Interestingly the variation between the individual results is larger for OPC cement, which is contrary to the observations at 28 days.

For the wall series the OPC/GGBS concrete yield a chloride conductivity of 0,24 mS/cm, OPC/FA concrete 0,17 mS/cm and OPC/CSF concrete 0,79 mS/cm. For the GGBS and FA concretes all of the results satisfy or exceed the "Excellent" durability category. For the CSF concrete the results range from "Excellent" to "Good".

Ignoring the results for samples cast using CEM I cement and broadly comparing the results for slabs and walls using OPC cement it is noted that as the water/binder ratio decreases (the quantity of binder increases) the chloride conductivity reduces (improved properties). OPC/FA concrete exhibited the least change in chloride conductivity with change in water/binder ratio while both OPC/GGBS and OPC/CSF concretes exhibited a larger change in chloride conductivity with change in water/binder ratio.

Interestingly the influence of the material properties is still evident at 120 days, however in this case it is not possible to comment on the spread of results given the absence of 120-day data from other current research data in South Africa.

5.1.3 CONCLUSIONS RELATING TO THE INFLUENCE OF WATER/BINDER RATIO

Based on the observations and discussion, the following can be concluded:

- To achieve a specified compressive strength the water/binder ratio can be increased by the use of CSF as a cement extender;
- The GGBS concretes exhibit noticeably lower results for chloride conductivity at 28 days, when compared with FA and CSF concretes. However at 120 days the chloride conductivity for FA concretes has reduced such that both GGBS and FA concretes exhibit essentially similar chloride conductivity, substantially lower than CSF concretes;
- The use of OPC cement resulted in lower chloride conductivity at 28 and 120 days, when compared with CEM I cement; and
- Change in water/binder ratio within the range of 0,57 to 0,46 has the effect of reducing the chloride conductivity, as the ratio is reduced, for fully water-cured concrete samples with OPC cement.

5.2 INFLUENCE OF BINDER TYPE

5.2.1 CHLORIDE CONDUCTIVITY RESULTS AT 28 DAYS

Figure 22 shows the chloride conductivity results for 28-day wet-cured cubes, plotted against the respective core compressive strengths for the three binder types.

In general the OPC/GGBS and OPC/FA concretes show improved (i.e. lower) chloride conductivity results. Given the absence of a full data set it is not possible to comment on all the concretes in this regard. The range in chloride conductivity results is very low over the range in compressive strengths shown for GGBS concretes (both OPC and CEM I cements), while both FA and CSF concretes exhibit a larger range in chloride conductivity results, with CSF the largest. The GGBS concrete also clearly exhibits the lowest (most favourable) chloride conductivity results and CSF concrete the highest (poorest).

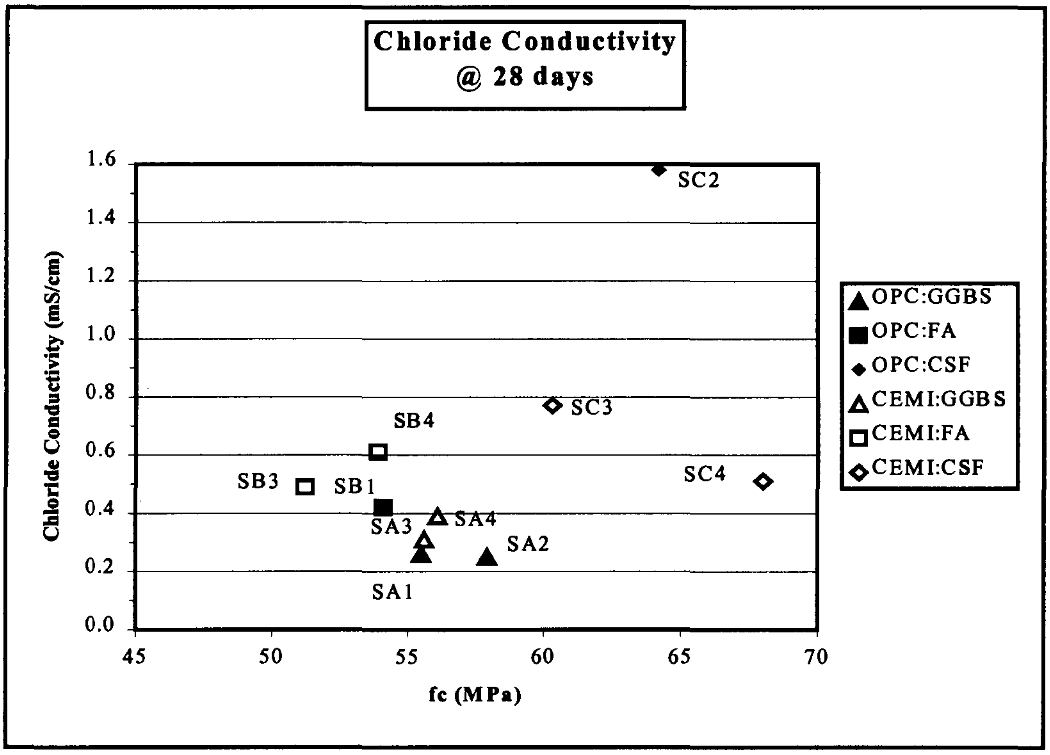


FIGURE 22: CHLORIDE CONDUCTIVITY RESULTS FOR 28-DAY WET-CURED CUBES, PLOTTED AGAINST 28-DAY COMPRESSIVE CORE STRENGTHS.

5.2.2 CHLORIDE CONDUCTIVITY RESULTS AT 120 DAYS

Figure 23 shows the chloride conductivity results for 120-day wet-cured concretes, plotted against the respective core compressive strengths for the three binder types.

In comparison with Figure 22, the range of chloride conductivity results reduces at the later age and lies in a lower band for GGBS and FA concretes. The chloride conductivity results for CSF concretes have exhibited a marginal change from 28-days to 120 days. The FA concretes exhibit the largest change in results with age such that they have reduced to be essentially indistinguishable from the GGBS concretes. This observation was also noted in the general research programme, currently underway at the Universities of Cape Town and Wits. It has been concluded that to undertake 28-day chloride conductivity determination for FA concretes, underestimates the potential durability of these concretes since the durability properties continue to develop with time, beyond 28 days. The OPC and CEM I cement results are clearly separated, with OPC cement yielding the lower (more favourable) results.

5.2.3 CONCLUSIONS RELATING TO THE INFLUENCE OF BINDER TYPE

Based on the observations and discussion the following can be concluded:

- The 28-day chloride conductivity results for GGBS concretes are the most favourable followed by the FA concretes, both falling within the "Excellent" durability category. The CSF concretes yield the poorest results at 28 days in the "Good" durability category;

- At 120 days the FA and GGBS concretes yield the lowest chloride conductivity results (all within the "Excellent" durability category) followed by CSF concretes, exhibiting substantially poorer results (in the "Good" durability category);
- For both 28-day and 120-day there was a marked shift between the results for OPC and CEM I cement, with OPC cements exhibiting the lower (more favourable) results; and
- The influence of binder type is evident for well-cured concretes in the strength ranges given. At 28 days the distinction between the three concretes is evident, however at 120 days the results for GGBS and FA concretes are "indistinguishable" with CSF concretes still exhibiting the noted distinction.

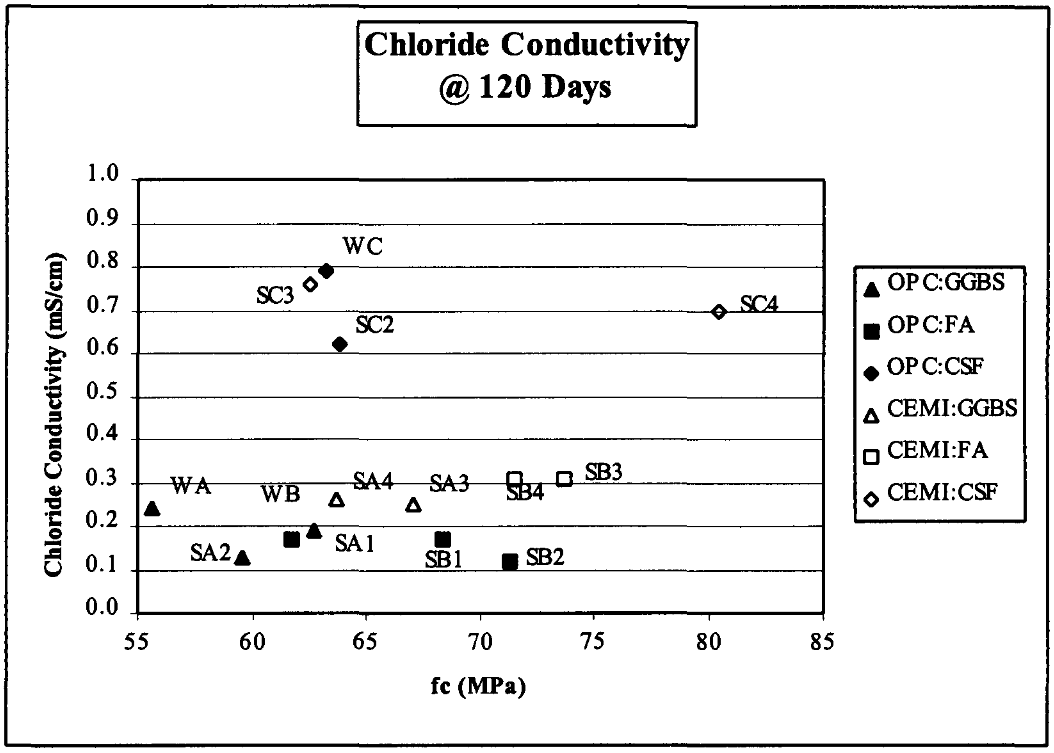


FIGURE 23: CHLORIDE CONDUCTIVITY RESULTS FOR 120-DAY WET-CURED CUBES, PLOTTED AGAINST 120-DAY COMPRESSIVE CORE STRENGTHS.

5.3 INFLUENCE OF ELEMENT AGE

5.3.1 GGBS CONCRETES

Table 26 shows the change in chloride conductivity with time for wet-cured cubes.

Figure 24 shows the 28-day and 120-day chloride conductivity results for the wet-cured cubes, plotted against the respective core compressive strengths for GGBS concretes. Note that for this figure both the OPC and CEM I are combined in a single legend.

TABLE 26: CHLORIDE CONDUCTIVITY RESULTS AT 28 AND 120 DAYS, FOR SLAB A SERIES.

ELEMENT	CHLORIDE CONDUCTIVITY @ 28 DAYS (mS/cm)	CHLORIDE CONDUCTIVITY @ 120 DAYS (mS/cm)
SLAB A1	0,26	0,19
SLAB A2	0,25	0,13
SLAB A3	0,36	0,25
SLAB A4	0,39	0,26

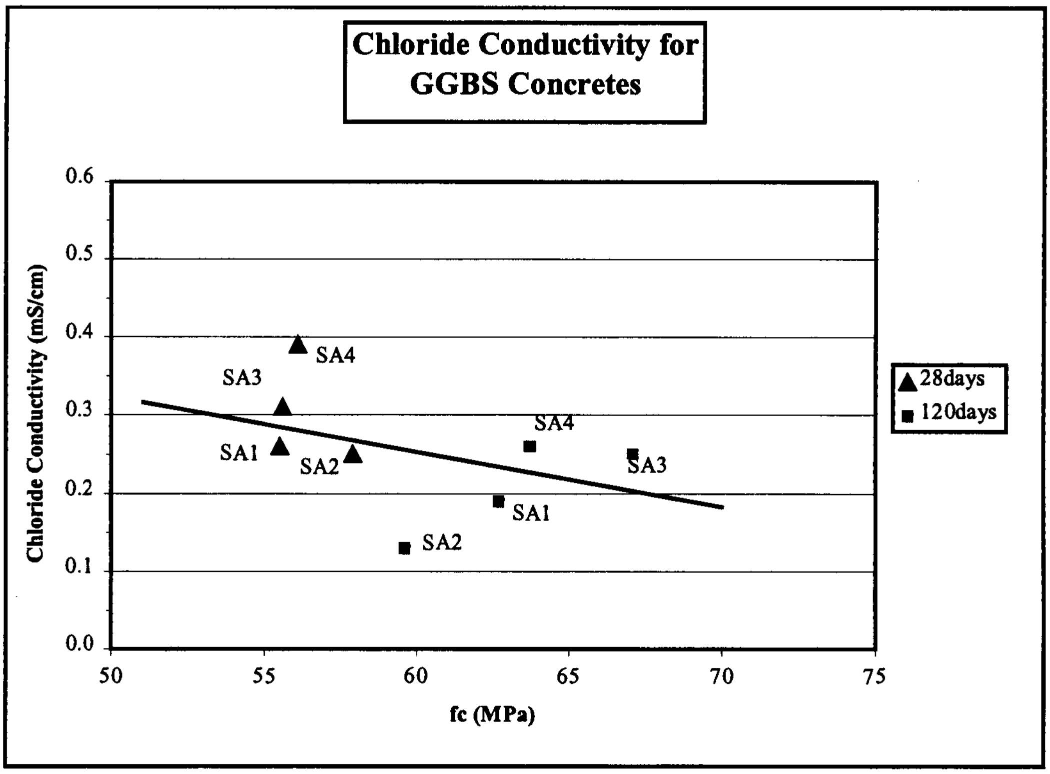


FIGURE 24: CHLORIDE CONDUCTIVITY RESULTS FOR GGBS CONCRETES AT 28 & 120 DAYS PLOTTED AGAINST RESPECTIVE COMPRESSIVE CORE STRENGTHS FOR WET-CURED CUBES.

For the GGBS concretes there is a marked trend of chloride conductivity reducing with increasing strength. In effect the chloride conductivity reduces with age, and the compressive strength increases with age, under fully water-cured conditions.

5.3.2 FA CONCRETES

Table 27 shows the change in chloride conductivity with time for wet-cured cubes.

For the FA concretes there is a marked trend of chloride conductivity reducing with a increasing strength. In effect the chloride conductivity reduces with age, and the compressive strength increases with age, under fully water-cured conditions.

TABLE 27: CHLORIDE CONDUCTIVITY RESULTS AT 28 AND 120 DAYS, FOR SLAB B SERIES.

ELEMENT	CHLORIDE CONDUCTIVITY @ 28 DAYS (mS/cm)	CHLORIDE CONDUCTIVITY @ 120 DAYS (mS/cm)
SLAB B1	0,42	0,17
SLAB B2	(Outlier)	0,12
SLAB B3	0,49	0,31
SLAB B4	0,61	0,31

Figure 25 shows the 28-day and 120-day chloride conductivity results for wet-cured cubes, plotted against the respective core compressive strengths for FA concretes. Note that for this figure both the OPC and CEM I are combined in a single legend.

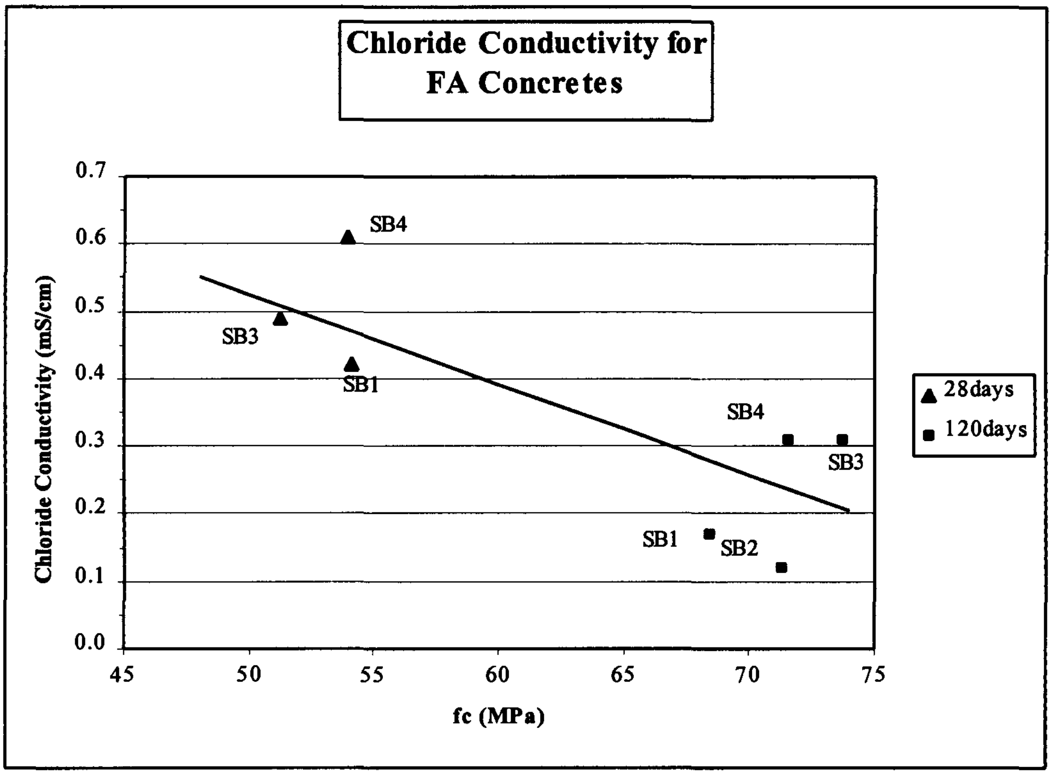


FIGURE 25: CHLORIDE CONDUCTIVITY RESULTS FOR FA CONCRETES AT 28 & 120 DAYS PLOTTED AGAINST RESPECTIVE COMPRESSIVE CORE STRENGTHS FOR WET-CURED CUBES.

5.3.3 CSF CONCRETES

Table 28 shows the change in chloride conductivity with time for wet-cured cubes.

Given the limited results, it appears that the chloride conductivity does not change appreciably with time from 28 days to 120 days - an observation that also holds true for compressive strength. The use of CSF as an extender induces more rapid hydration in the first 28 days with little change thereafter. The compressive strength result for slab C4 at 120 days appears somewhat questionable in that it has increased substantially from 28 days to 120 days.

TABLE 28: CHLORIDE CONDUCTIVITY RESULTS AT 28 AND 120 DAYS, FOR SLAB C SERIES.

ELEMENT	CHLORIDE CONDUCTIVITY @ 28 DAYS (mS/cm)	CHLORIDE CONDUCTIVITY @ 120 DAYS (mS/cm)
SLAB C1	No data	0,55
SLAB C2	1,58	0,62
SLAB C3	0,77	0,76
SLAB C4	0,51	0,70

Figure 26 shows the 28-day and 120-day chloride conductivity results for wet-cured cubes, plotted against the respective core compressive strengths for CSF concretes. Note that for this figure both the OPC and CEM I are combined in a single legend. While the result for SC2 at 28 days was evaluated to be statistically acceptable, in developing a linear regression it represented a discontinuity. It was thus decided to ignore this result for the purposes of this evaluation.

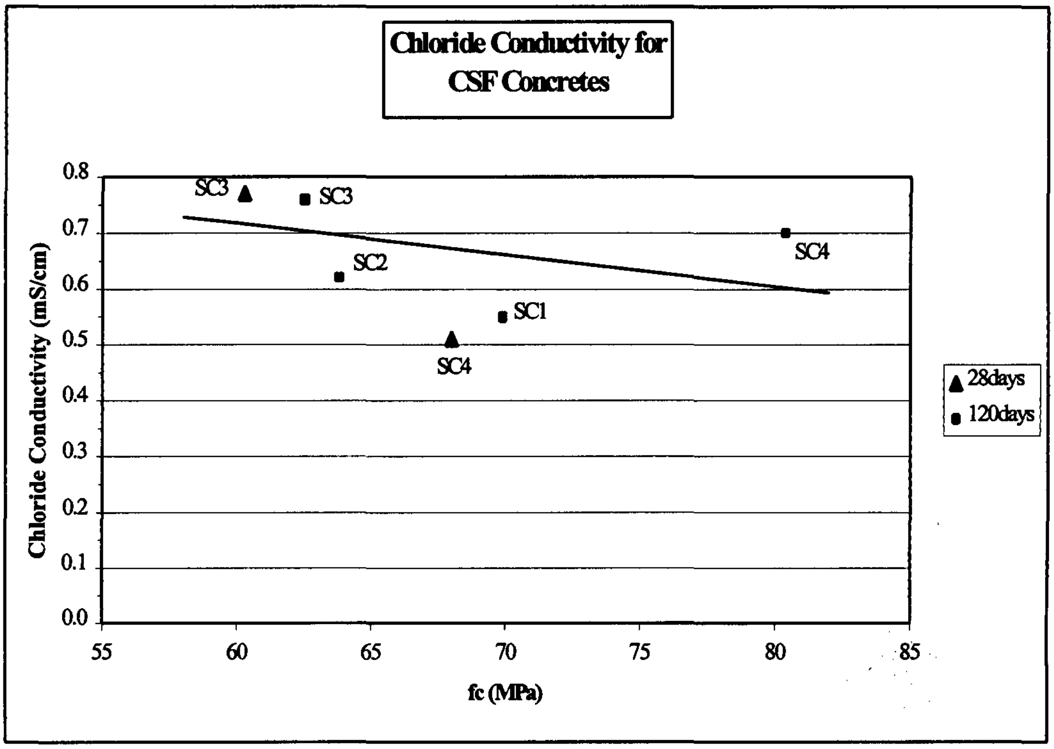


FIGURE 26: CHLORIDE CONDUCTIVITY RESULTS FOR CSF CONCRETES AT 28 & 120 DAYS PLOTTED AGAINST RESPECTIVE COMPRESSIVE CORE STRENGTHS FOR WET-CURED CUBES.

Given the degree of scatter in the results, there is a marked trend of chloride conductivity reducing with age, coupled with an increase in compressive strength with age, depending on concrete type. In comparison to the GGBS and CSF concretes a much larger increase in compressive strength is evident for FA concretes. GGBS concretes exhibited an increase of approximately 10 MPa, CSF concretes remained effectively unchanged while FA concretes exhibited an increase of about 20 MPa, over a period from 28 days to 120 days.

5.3.4 CONCLUSIONS RELATING TO THE INFLUENCE OF ELEMENT AGE

Based on the observations and discussion the following can be concluded:

- The FA and GGBS concretes show a definite trend of chloride conductivity reducing with time (from about 0,30 mS/cm to 0,20 mS/cm for GGBS concretes and from about 0,50 mS/cm to 0,25 mS/cm for FA concretes). Clearly the FA concretes exhibit a more noticeable reduction. While the results for the individual elements were scattered, the general trend is well established. Compressive strength also increased substantially with time for FA and GGBS concretes;
- The results for the CSF concretes exhibit very little change with time, for either chloride conductivity or compressive strength; and
- Given the scatter in data it is not possible to comment on the effect of the change in cement specification (OPC vs. CEM I) on the chloride conductivity results with time.

5.3.5 GENERAL CONCLUSIONS RELATING TO FULLY WATER CURED SAMPLES

Based on the observations and discussion in the proceeding three sections of this chapter the following can be concluded, relative to fully water-cured samples, and considered as the key findings for the first sections of this chapter:

- The GGBS concretes produce the lowest chloride conductivity results at both 28 days and 120 days, within the "Excellent" durability category for both OPC and CEM I cements, with OPC cement yielding marginally lower chloride conductivity results. The chloride conductivity results for this concrete exhibit the definite trend of reducing with time. Given the scatter of the results and the size of the data set it is not possible to comment on the effect of the change in cement specification on this trend;
- The chloride conductivity for FA concretes was noticeably higher in comparison with the GGBS concrete at 28 days, however still within the "Excellent" durability category for both OPC and CEM I cements, with OPC cement yielding lower chloride conductivity results. However at 120 days the chloride conductivity for FA concretes has reduced to be virtually indistinguishable from the GGBS concrete results for both OPC and CEM I cements, with OPC cement once again yielding marginally lower chloride conductivity results. As for GGBS concrete FA concrete exhibits the trend of the chloride conductivity reducing with time, but far more noticeably than GGBS and CSF concretes. For reasons as set out above it is not possible to comment on the effect of the change in cement specification on this trend; and
- The CSF concretes consistently produce the highest chloride conductivity results at both 28 days and 120 days, within the "Good" durability category for both OPC and CEM I cements, with OPC cement yielding marginally lower chloride conductivity results. CSF concrete exhibits very little change in chloride conductivity with time, and the comments in the above sections regarding the change in cement specification hold true for CSF concrete.

5.4 INFLUENCE OF CURING METHOD

5.4.1 WALL SERIES

5.4.1.1 28-Day Results

Figure 27 shows the 28-day chloride conductivity results for the OPC/GGBS (Wall A) concrete (together with the environmental rating), with reference to the various curing methods. No data was available for Wall B and Wall C, hence they are not reflected here.

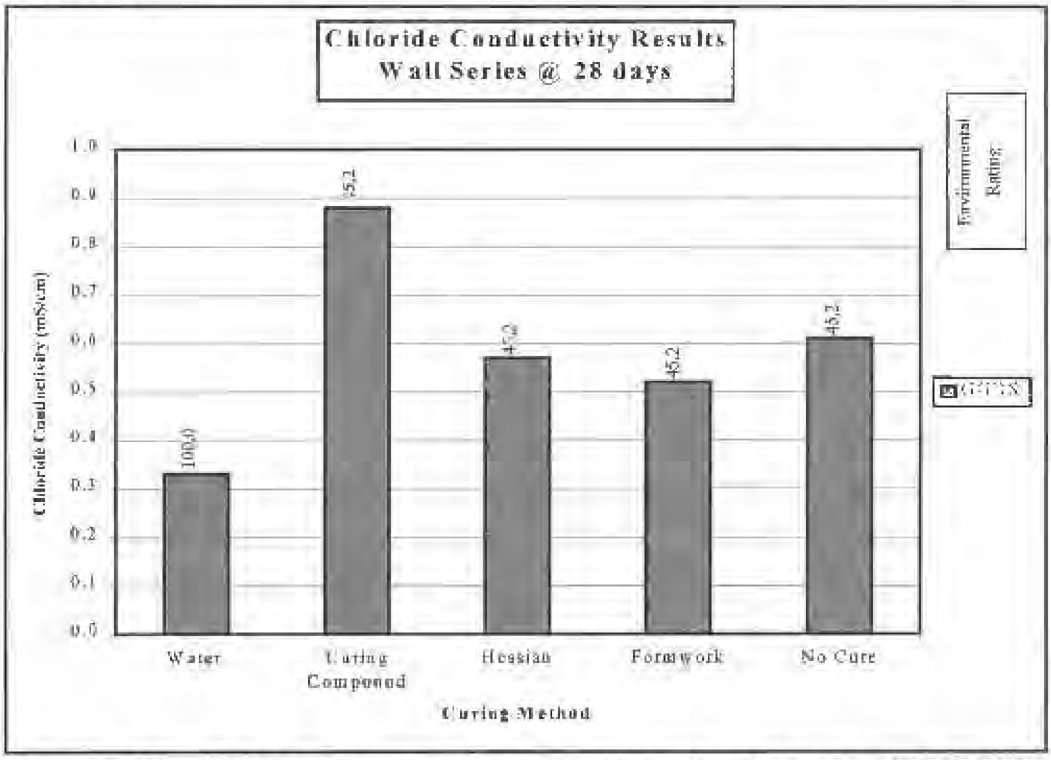


FIGURE 27: 28-DAY CHLORIDE CONDUCTIVITY RESULTS FOR OPC/GGBS CONCRETE (TOGETHER WITH THE ENVIRONMENTAL RATING), WITH REFERENCE TO THE VARIOUS CURING METHODS.

From Figure 27, it is evident that as the environmental rating decreases the chloride conductivity increases. This observation is consistent for all the curing methods and indicates that the chloride conductivity is affected by curing.

The 28-day chloride conductivity results for OPC/GGBS concrete are detailed in Table 29.

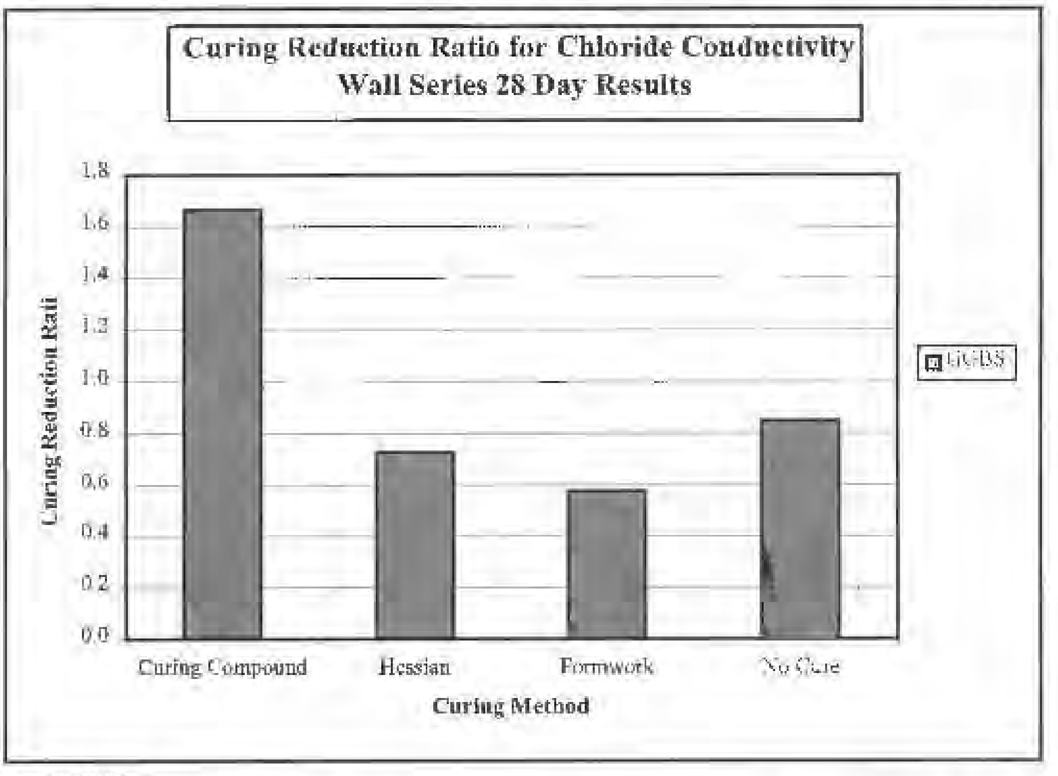
TABLE 29: 28-DAY CHLORIDE CONDUCTIVITY RESULTS FOR OPC/GGBS CONCRETES PER CURING METHOD.

CURING METHOD	CHLORIDE CONDUCTIVITY (mS/cm)	CURING REDUCTION RATIO
WATER	0,33	
COMPOUND	0,88	1,67
HESSIAN	0,57	0,73
FORMWORK	0,52	0,58
UNCURED	0,61	0,85

The results show that, with the exception of curing compound curing, the chloride conductivity results for the OPC/GGBS concretes fall broadly within the "Excellent" durability category. For curing compound curing the chloride conductivity results fall inside the "Good" durability category.

Figure 28 shows the change in 28-day chloride conductivity results for the various curing methods, for OPC/GGBS concrete. The figure uses a "curing reduction ratio" which is the difference between the chloride conductivity under consideration (site-curing methods) and the wet-cured condition divided by the wet-cured condition. Thus the larger a particular "curing reduction ratio", the larger the shift between the fully cured chloride conductivity value and the chloride conductivity value for the site-curing method under consideration.

For the OPC/GGBS concretes the ratios can be broadly grouped. The curing compound curing yields the highest ratio while the formwork, hessian and no active curing methods yield smaller roughly equal ratios. The common factor between formwork, hessian and no active curing is that they do not provide an impenetrable moisture barrier while curing compound curing possibly does. This is particularly relevant to this element since it received substantial early age



precipitation.

FIGURE 28: CHANGE IN 28-DAY CHLORIDE CONDUCTIVITY RESULTS FOR WALL SERIES PLOTTED AGAINST RESPECTIVE CURING METHOD.

Alexander et al[34] indicated that for uncured Western Cape concretes consisting of a blend of OPC/GGBS of the same concrete grade, in the same proportions as used in this project, chloride conductivity results in the region of 2,00 mS/cm were realised. Interestingly the chloride conductivity results achieved in this study are of the order of two times smaller (more favourable), indicating firstly a better site-curing environment and secondly possibly a better combination of materials (fine and course aggregate fraction).

5.4.1.2 Conclusions Relating to 28-Day Results

Based on the observations and discussion and subject to the environmental conditions experienced by the wall elements, the following can be concluded:

- At 28-day element age, the chloride conductivity is affected by the curing method utilised;
- For the OPC/GGBS concretes the chloride conductivity results at 28-day element age for the site-curing methods fall within the "Excellent" durability category, with the exception of curing compound curing which is within the "Good" durability category; and
- The use of hessian and formwork retention as curing methods is more beneficial than the application of curing compound for OPC/GGBS concretes. Depending on the environmental conditions at time of casting it is possible that the application of curing compound is more detrimental to early age properties than no active curing (as is the case for wall A). In the event of early age precipitation (within the first 1 to 3 days after casting, as was experienced with wall A) the curing compound excludes the free moisture from penetrating the covercrete, while no curing does not.

5.4.1.3 120-Day Results

Figure 29 shows the 120-day chloride conductivity results for the OPC/GGBS (Wall A), OPC/FA (Wall B) and OPC/CSF (Wall C) concretes (together with the environmental rating), plotted against curing method.

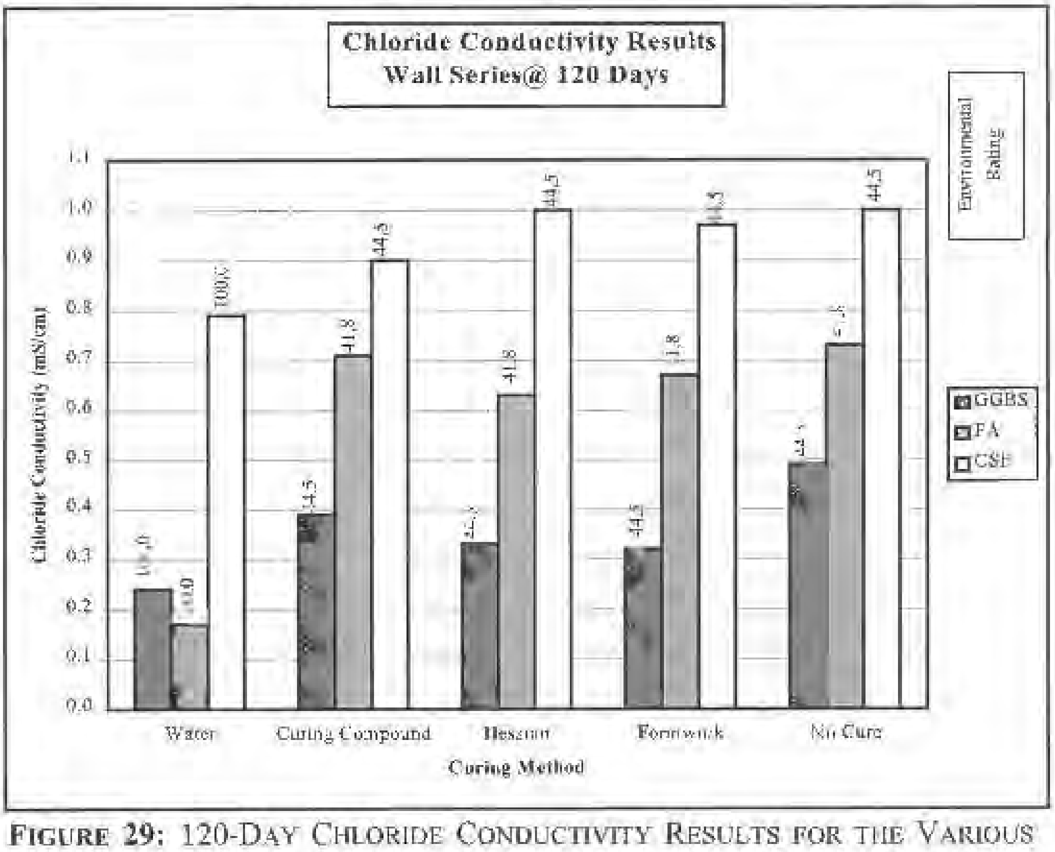


FIGURE 29: 120-DAY CHLORIDE CONDUCTIVITY RESULTS FOR THE VARIOUS CONCRETES (TOGETHER WITH THE ENVIRONMENTAL RATING), WITH REFERENCE TO THE DIFFERENT CURING METHODS.

The 120-day chloride conductivity results for OPC/GGBS concrete are detailed in Table 30.

TABLE 30: 120-DAY CHLORIDE CONDUCTIVITY RESULTS FOR OPC/GGBS CONCRETE PER CURING METHOD.

CURING METHOD	CHLORIDE CONDUCTIVITY (mS/cm)	CURING REDUCTION RATIO
WATER	0,24	
COMPOUND	0,39	0,63
HESSIAN	0,33	0,38
FORMWORK	0,32	0,33
UNCURED	0,49	1,04

The chloride conductivity results for the OPC/GGBS concrete fall within the "Excellent" durability category. Considering the change in chloride conductivity with time (using the 120-day data as base) decreases of the order of 30 % to 70 % have occurred for the site elements, while for the wet-cured cubes the decrease is about 40%.

The 120-day chloride conductivity results for OPC/FA concrete are detailed in Table 31.

TABLE 31: 120-DAY CHLORIDE CONDUCTIVITY RESULTS FOR OPC/FA CONCRETE CURING METHOD.

CURING METHOD	CHLORIDE CONDUCTIVITY (mS/cm)	CURING REDUCTION RATIO
WATER	0,17	
COMPOUND	0,71	3,18
HESSIAN	0,63	2,71
FORMWORK	0,67	2,94
UNCURED	0,73	3,29

The chloride conductivity results for the OPC/FA concrete fall within the "Excellent" durability category, although marginally larger than the OPC/GGBS concrete.
The 120-day chloride conductivity results for OPC/CSF concrete are detailed in Table 32.

TABLE 32: 120-DAY CHLORIDE CONDUCTIVITY RESULTS FOR OPC/CSF CONCRETE PER CURING METHOD.

CURING METHOD	CHLORIDE CONDUCTIVITY (mS/cm)	CURING REDUCTION RATIO
WATER	0,79	
FORMWORK	0,90	0,14
HESSIAN	1,00	0,27
COMPOUND	0,97	0,23
UNCURED	1,00	0,27

The chloride conductivity for the OPC/CSF concrete falls within the "Good" durability category, for all of the curing methods. For the full wet-cured condition, OPC/FA concrete yielded the lowest chloride conductivity (0,17 mS/cm), followed by OPC/GGBS concrete (0,24 mS/cm) and OPC/CSF concrete (0,79 mS/cm). The OPC/GGBS and OPC/FA concretes fall well within the "Excellent" durability category, while the OPC/CSF concretes fall within the "Good" durability category.

For the formwork, hessian, curing compound and no-curing conditions the chloride conductivity results for OPC/GGBS concrete exhibit a small range (0,32 mS/cm to 0,49 mS/cm), and fall into the "Excellent" durability category. These are the lowest chloride conductivity results for the wall series data. OPC/FA concrete results follow this, also exhibiting a small range (0,63 mS/cm to 0,73 mS/cm), and fall into the "Excellent" durability category. For the OPC/CSF concrete the chloride conductivity results are slightly higher and exhibit a similar spread to those of the OPC/GGBS concrete and OPC/FA concrete (0,90 mS/cm to 1,00 mS/cm), and fall into the "Good" durability category.

Figure 30 shows the change in 120-day chloride conductivity results for the various curing methods, for the OPC/GGBS, OPC/FA and OPC/CSF concrete.
The figure uses a "curing reduction ratio" which is the difference between the chloride conductivity under consideration (site-curing methods) and the fully water-cured condition divided by wet-cured condition. Thus the higher a particular "curing reduction ratio", the larger the shift between the fully cured chloride conductivity value and the chloride conductivity value for the site-curing method under consideration.

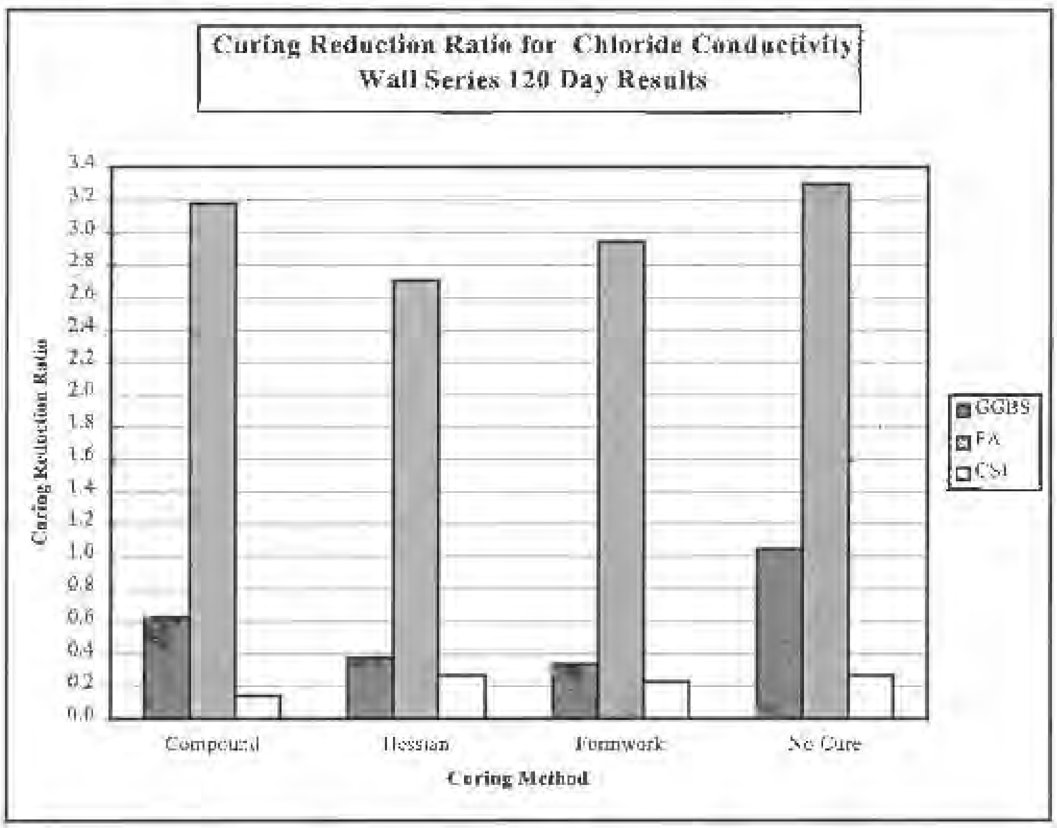


FIGURE 30: CHANGE IN 120 DAY CHLORIDE CONDUCTIVITY RESULTS FOR WALL SERIES PLOTTED AGAINST RESPECTIVE CURING METHOD.

Considering the data presented in Figure 30, OPC/FA concrete exhibited noticeably the highest "curing reduction ratio" in chloride conductivity per curing method and is an indication of the sensitivity of the OPC/FA concrete to curing.

By contrast, the OPC/GGBS and OPC/CSF concretes yielded a lower "curing reduction ratio" for chloride conductivity per curing method and is an indication of the reduced sensitivity of these concretes to curing.

Hessian and formwork retention are nominally "better" site-curing methods than curing compound and no curing, for both GGBS and FA concretes. The CSF concrete however exhibits a very similar range of "curing reduction ratios" per site-curing method, indicating it's reduced sensitivity to curing mainly due to the early hydration typical of these types of concretes.

5.4.1.4 Conclusions Relating to 120-Day Element Age Results

Based on the observations and discussion the following can be concluded:

- At 120-day element age, the chloride conductivity is affected by the curing method utilised;
- For OPC/GGBS and OPC/FA concretes the chloride conductivity results at 120-day element age for the site-curing methods fall within the "Excellent" durability category. For OPC/CSF concrete the results fall within the "Good" durability category;
- OPC/FA concrete exhibited the largest "curing reduction ratio" for chloride conductivity per curing method. OPC/CSF and OPC/GGBS concretes exhibited a similar but smaller "curing reduction ratio" for chloride conductivity per curing method; and
- The use of hessian and formwork retention as curing methods is more beneficial than the application of curing compound for OPC/GGBS and OPC/FA concretes. In addition for these two concretes no curing results in the largest chloride conductivity at 120 days. For CSF concrete no site-curing method emerged as more beneficial than another with essentially equal influence on the durability properties developed.

5.4.1.5 General Conclusions Relating to Site-Cured Wall Samples

Based on the observations and discussion in the preceding section of this chapter the following can be concluded, relative to site-cured wall samples. These are considered as the key findings for this part of the this chapter:

- OPC/GGBS concrete in walls exhibited definite sensitivity to curing at both 28 days and 120 days. At 28 days the chloride conductivity for various site-cured samples are within the "Excellent" and "Good" durability category, while at 120 days all the results are within the "Excellent" durability category. The use of hessian and formwork retention as curing methods is more beneficial than the application of curing compound for OPC/GGBS concretes at both 28 days and 120 days;
- OPC/FA concrete exhibited a substantial sensitivity to curing for chloride conductivity per curing method at 120 days, and was the most sensitive of the three concretes used. Due to the absence of a data set at 28 days it is not possible to comment on results at this age. At 120 days the chloride

conductivity for various site-cured samples are within the "Excellent" durability category. The use of hessian and formwork retention as curing methods is more beneficial than the application of curing compound for OPC/FA concretes at 120 days; and

- OPC/CSF concrete exhibited the least sensitivity to curing for chloride conductivity per curing method at 120 days, of the three concretes used. Due to the absence of a data set at 28 days it is not possible to comment on results at this age. At 120 days the chloride conductivity for various site-cured samples are within the "Excellent" and "Good" durability category. No site-curing method emerged as more beneficial than another with essentially equal influence on the durability properties developed.

5.4.2 Slab Series

5.4.2.1 28-Day Results

The data are discussed for the elements cast using OPC and CEM I separately. The slab series 1&2 were cast using OPC cement while series 3&4 were cast using CEM I cement.

5.4.2.2 Observations and Discussion: Series Cast Using OPC Blends

Figure 31 shows the 28-day chloride conductivity results for the OPC/GGBS (slab A1 and A2), OPC/FA (slab B1 and B2) and OPC/CSF (slab C2) concretes (together with environmental rating), with reference to the curing methods. No results are shown for slab C1 since this data was not available.

The 28-day chloride conductivity results for the OPC/ GGBS concrete are given in Table 33.

Table 33: 28-Day Chloride Conductivity Results for OPC/GGBS Concrete Per Curing Method.

Curing Method	Chloride Conductivity (Slab A1 Series) mS/cm	Chloride Conductivity (Slab A2 Series) mS/cm	Mean Chloride Conductivity mS/cm	Mean Curing Reduction Ratio
Water	0,26	0,25	0,26	
Compound	0,36	0,33	0,35	0,35
Hessian	0,35	0,41	0,38	0,46
Sand	0,36	0,25	0,31	0,19
Uncured	0,35	0,34	0,35	0,35

All the results are fairly similar and fall in a narrow band, generally within the "Excellent" durability category. Sand curing is the most effective site-curing method followed by the application of curing compound, no active curing and hessian curing (in order of effectiveness). Very little variation is evident between the various site-cured results and they effectively yield the same durability properties in terms of chloride conductivity.

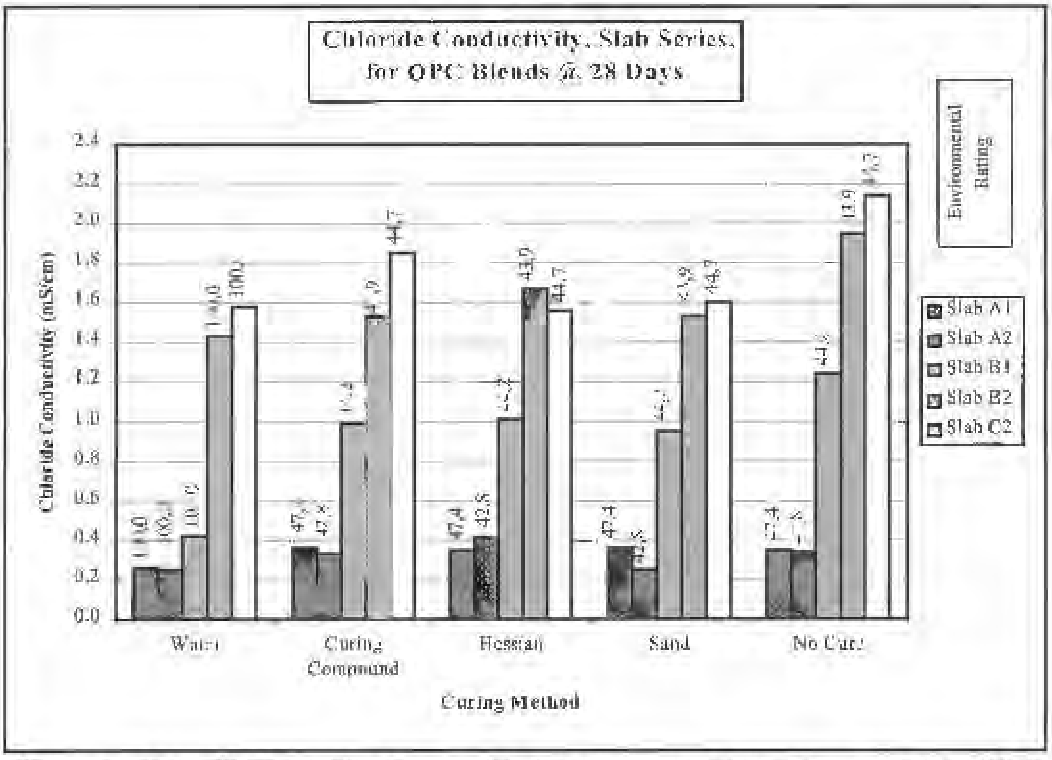


FIGURE 31: 28-DAY CHLORIDE CONDUCTIVITY RESULTS AT FOR OPC CONCRETES (TOGETHER WITH THE ENVIRONMENTAL RATING), PLOTTED AGAINST VARIOUS CURING METHODS.

The 28-day chloride conductivity results for the OPC/ FA concrete are given in Table 34.

TABLE 34: 28-DAY CHLORIDE CONDUCTIVITY RESULTS FOR OPC/FA CONCRETE PER CURING METHOD.

CURING METHOD	CHLORIDE CONDUCTIVITY (SLAB B1 SERIES) mS/cm	CHLORIDE CONDUCTIVITY (SLAB B2 SERIES) mS/cm	MEAN CHLORIDE CONDUCTIVITY mS/cm	MEAN CURING REDUCTION RATIO
WATER	0,42	(Outlier)	0,42	
COMPOUND	0,99	1,53	1,26	2,00
HESSIAN	1,01	1,67	1,34	2,19
SAND	0,95	1,53	1,24	1,95
UNCURED	1,24	1,95	1,60	2,80

The value for 28-day wet curing is within the "Excellent" durability category, while the remainder of the results are within the "Good" durability category, with no curing yielding the highest result (poorest properties). This re-iterates the previous finding of the sensitivity of the OPC/FA concrete to curing. As for OPC/GGBS concretes sand curing proves to be the most effective site-curing method, followed by the application of curing compound, hessian curing and no curing (in order of effectiveness). In this case there is a significant variation between the lowest and highest chloride conductivity result for the site-cured concrete.

The 28-day Chloride Conductivity results for the OPC/CSF concrete are given in Table 35.

TABLE 35: 28-DAY CHLORIDE CONDUCTIVITY RESULTS FOR OPC/CSF CONCRETE PER CURING METHOD.

CURING METHOD	CHLORIDE CONDUCTIVITY (SLAB C1 SERIES) mS/cm	CHLORIDE CONDUCTIVITY (SLAB C2 SERIES) mS/cm	MEAN CHLORIDE CONDUCTIVITY mS/cm	MEAN CURING REDUCTION RATIO
WATER	No data	1,58	1,58	
COMPOUND	No data	1,85	1,85	0,19
HESSIAN	No data	1,56	1,56	*
SAND	No data	1,60	1,60	0,02
UNCURED	No data	2,14	2,14	0,37

* *Indicates a negative value.*

All the 28-day values are within the "Poor" durability category. Hessian curing proves to be the most effective site-curing method, followed by sand curing, the application of curing compound and no active curing (in order of effectiveness). In this case there is a substantial variation between the lowest and highest chloride conductivity result for the site-cured concrete.

When comparing the uncured results for the above three concretes with currently available chloride conductivity data, from the Western Cape, for 28-day uncured samples, it was noted that the GGBS concretes in this study exhibited markedly improved results (of the order of six times smaller). Similarly the FA concretes exhibited noticeably improved results (of the order of two times smaller).

Alexander et al[34] reported chloride conductivity data for Western Cape OPC/CSF concretes in the range of 0,50 mS/cm to 0,70 mS/cm for three days of wet curing. For 28-days of wet curing they reported results of the order of 0,50 mS/cm. The results recorded here are of the order of three times poorer than the Western Cape concretes.

Figure 32 shows the mean change in 28-day chloride conductivity results for the various curing methods, and different concretes cast using OPC cement and is based on mean curing reduction ratio as presented in Tables 32 through 35.

OPC/FA concrete exhibited the highest "curing reduction ratio" in comparison to OPC/GGBS and OPC/CSF concretes, indicating the sensitivity of OPC/FA concrete to curing. The OPC/FA concretes indicate that sand and curing compound curing are marginally more effective than hessian curing, with no active curing the most ineffective. The OPC/GGBS concrete exhibits a similar trend, however the "curing reduction ratio" is noticeably reduced i.e. less sensitive to curing. The OPC/CSF concrete exhibits a reduced sensitivity to curing, similar to the OPC/GGBS concrete, with sand and hessian curing developing essentially the same results as wet curing; curing compound curing and no active curing produce marginally larger "curing reduction ratios".

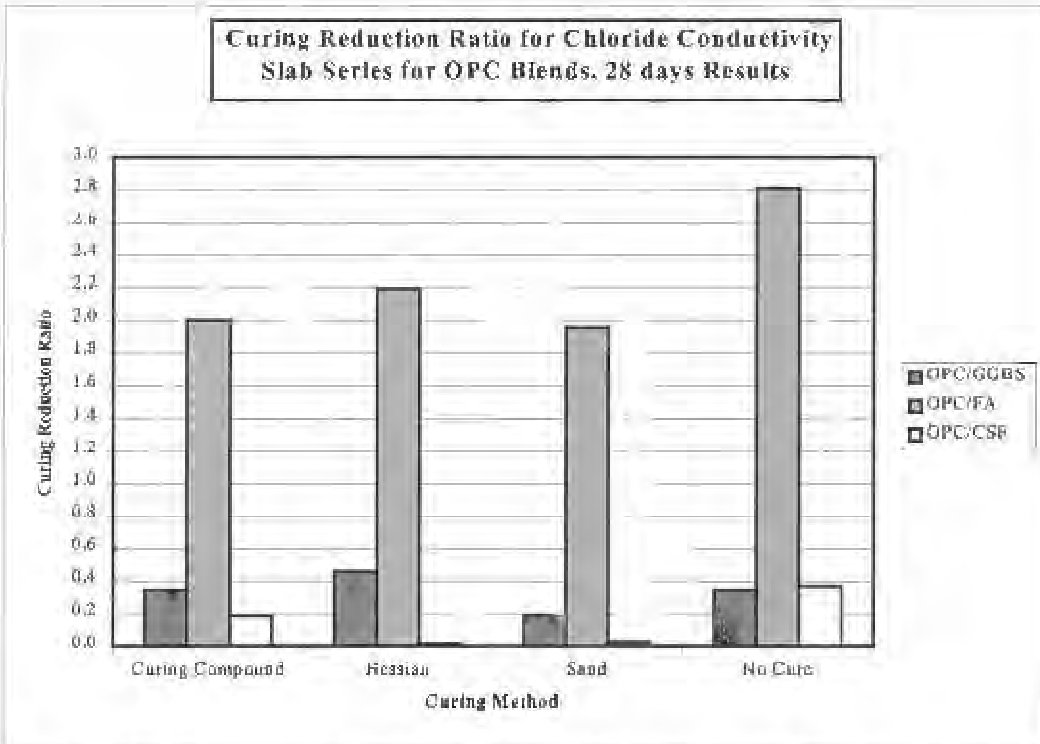


FIGURE 32: CHANGE IN 28-DAY CHLORIDE CONDUCTIVITY RESULTS FOR SLAB SERIES CAST USING OPC, PLOTTED AGAINST RESPECTIVE CURING METHOD.

While OPC/FA concrete indicates more sensitivity to curing when compared to OPC/GGBS concrete, it must be noted that this set of results represent "Good" durability properties.

5.4.2.3 Observations and Discussion: Series Cast Using CEM I Blends

Figure 33 shows the 28-day chloride conductivity results for the CEMI/GGBS (slab A3 and A4), CEMI/FA (slab B3 and B4) and CEMI/CSF (slab C3 and C4) concretes (together with environmental rating), with reference to the curing methods.

The 28-day Chloride Conductivity results for the GGBS/CEM I concrete are given in Table 36.

TABLE 36: 28-DAY CHLORIDE CONDUCTIVITY RESULTS FOR CEM I/GGBS CONCRETE PER CURING METHOD.

CURING METHOD	CHLORIDE CONDUCTIVITY (SLAB A3 SERIES) mS/cm	CHLORIDE CONDUCTIVITY (SLAB A4 SERIES) mS/cm	MEAN CHLORIDE CONDUCTIVITY mS/cm	MEAN CURING REDUCTION RATIO
WATER	0,31	0,26	0,29	
COMPOUND	0,62	0,37	0,50	0,71
HESSIAN	0,48	0,33	0,41	0,41
SAND	0,29	0,34	0,32	0,10
UNCURED	0,65	0,41	0,53	0,83

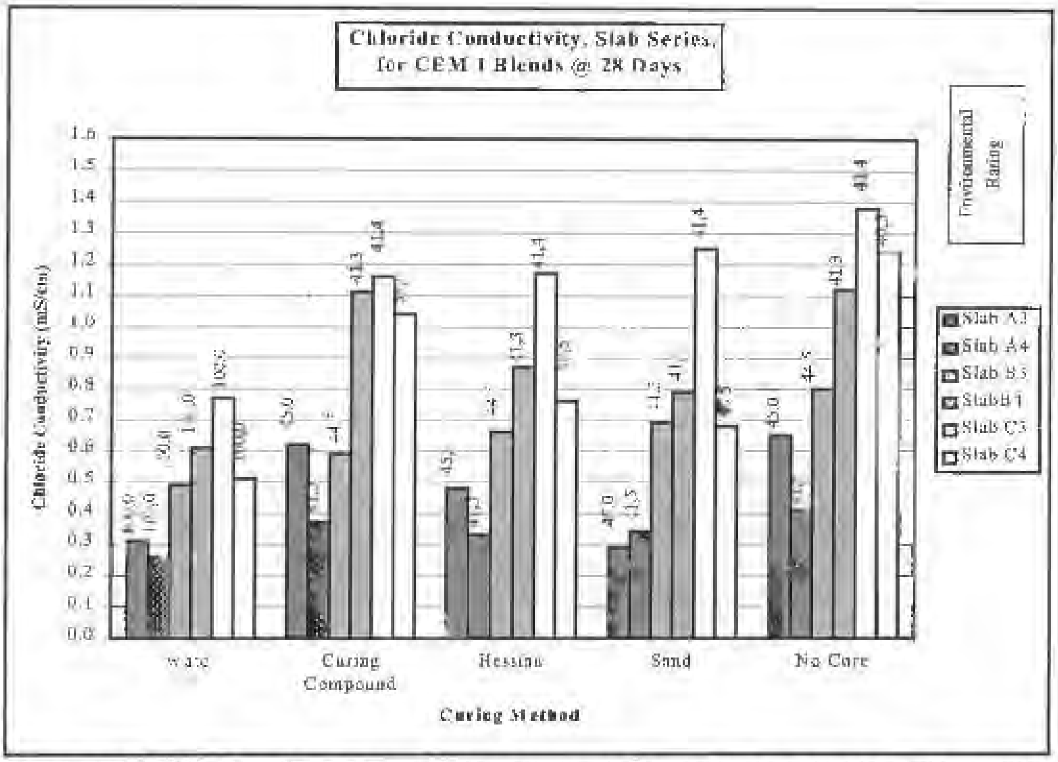


FIGURE 33: 28-DAY CHLORIDE CONDUCTIVITY RESULTS FOR CEM I CONCRETES (TOGETHER WITH THE ENVIRONMENTAL RATING), PLOTTED AGAINST VARIOUS CURING METHODS.

While all the result are within the "Excellent" durability category, the result for full wet-curing is noticeably lower, with no active curing yielding the highest result (poorest properties). Sand curing is the most effective site-curing method followed by hessian curing, the application of curing compound and no active curing (in order of effectiveness). Substantial variation is evident between the various site-cured results, however they are all within the "Excellent" durability category. When these results are compared to the OPC cement results (slab A1 and A2), at the same element age, it is noted that generally the CEM I consistently produced nominally higher results (poorer properties).

The 28-day chloride conductivity results for the CEM I/FA concrete are given in Table 37.

TABLE 37: 28-DAY CHLORIDE CONDUCTIVITY RESULTS FOR CEM I/FA CONCRETE PER CURING METHOD.

CURING METHOD	CHLORIDE CONDUCTIVITY (SLAB B3 SERIES) mS/cm	CHLORIDE CONDUCTIVITY (SLAB B4 SERIES) mS/cm	MEAN CHLORIDE CONDUCTIVITY mS/cm	MEAN CURING REDUCTION RATIO
WATER	0,49	0,61	0,55	
COMPOUND	0,59	1,11	0,85	0,55
HESSIAN	0,66	0,87	0,77	0,40
SAND	0,69	0,79	0,74	0,35
UNCURED	0,80	1,12	0,96	0,75

The results for wet curing and sand curing are within the "Excellent" durability category, while the remainder of the results are within the "Good" durability category, with no active curing yielding the highest (poorest properties) result. Sand curing is the most effective site-curing method followed by hessian curing, curing compound curing and no active curing (in order of effectiveness). A marginal variation is evident between the various site-cured results, however they are all within the "Excellent" and "Good" durability category. When these results are compared to the OPC concrete results (slab B1 and B2), at the same element age, it is noted that generally for CEM I concrete all the site-curing methods produce lower (more favourable properties).

The 28-day chloride conductivity results for the CEM I/CSF concretes are given in Table 38.

TABLE 38: 28-DAY CHLORIDE CONDUCTIVITY RESULTS FOR CEM I/CSF CONCRETE PER CURING METHOD.

CURING METHOD	CHLORIDE CONDUCTIVITY (SLAB C3 SERIES) mS/cm	CHLORIDE CONDUCTIVITY (SLAB C4 SERIES) mS/cm	MEAN CHLORIDE CONDUCTIVITY mS/cm	MEAN CURING REDUCTION RATIO
WATER	0,77	0,51	0,64	
COMPOUND	1,16	1,04	1,10	0,72
HESSIAN	1,17	0,76	0,97	0,51
SAND	1,25	0,68	0,97	0,51
UNCURED	1,38	1,24	1,31	1,05

The results for wet-curing are within the "Excellent" durability category, with the remainder of the results in the "Good" durability category, with no active curing yielding the highest result (poorest properties). Sand and hessian curing are the most effective site-curing methods, followed by curing compound curing and no active curing (in order of effectiveness). Variation is evident between the various site-cured results. When these results are compared to the OPC concrete results (slab C1 and C2), at the same element age, it is noted that generally for CEM I concrete all the site-curing methods produce lower (more favourable properties).

When comparing the above data with currently available chloride conductivity data, from the Western Cape, for 28-day uncured samples, it was noted that the GGBS concretes exhibited markedly improved results (of the order of four times smaller). Similarly the FA concretes exhibited noticeably improved results (of the order of two times smaller). For the CSF concrete however no uncured results were available, but the 28-day wet-cured correlate well with the data presented here.

Figure 34 shows the mean change in 28-day chloride conductivity results for the various curing methods, and different concretes cast using CEM I cement and is based on mean curing reduction ratio as presented in Tables 31 through 33.

In this case all the concretes exhibit a similar range of "curing reduction ratios" with CEM I/GGBS concrete indicating the largest range (of the order of 0,1 to 0,7).

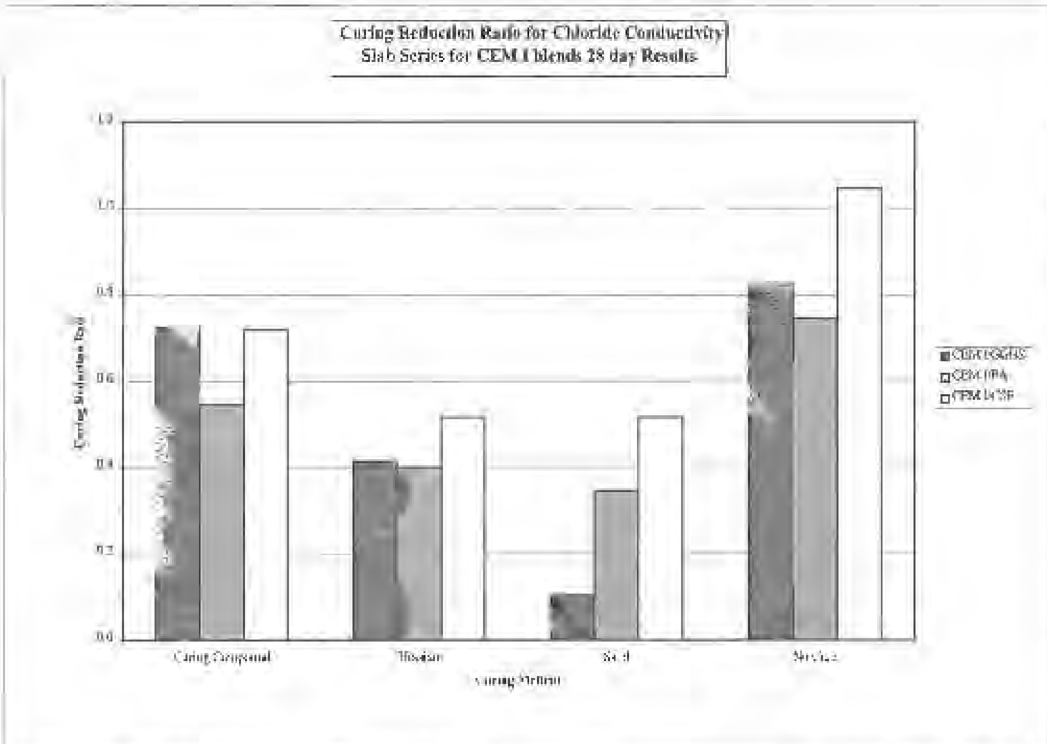


FIGURE 34: CHANGE IN 28-DAY CHLORIDE CONDUCTIVITY RESULTS FOR SLAB SERIES CAST USING CEM I, PLOTTED AGAINST RESPECTIVE CURING METHOD.

CEM I/GGBS concrete indicates that sand curing is the most effective site-curing method, noticeably more effective than hessian curing, followed by curing compound curing and no active curing, shown to be the most ineffective. CEM I/FA concretes show that sand curing is marginally more beneficial than hessian curing, followed by curing compound curing and no active curing (in order of effectiveness). For CEM I/CSF concretes sand and hessian curing are shown to be similar in terms of curing effectiveness, followed by curing compound curing and no active curing, with a noticeable increase in "curing reduction ratio" between curing compound curing and no active curing.

By comparison with the OPC cement the use of CEM I cement with GGBS has resulted in a substantial increase in curing reduction ratio for the application of curing compound and no active curing, while sand and hessian curing remained markedly consistent. For FA concrete the use of CEM I cement has resulted in a substantial reduction in curing reduction ratio for all the site-curing methods. For CSF concretes the use of CEM I has resulted in a substantial increase in the curing reduction ratio for all the site-curing methods.

5.4.2.4 Conclusions Relating to 28-Day Results

Based on the observation and discussion and subject to the environmental conditions experienced by the elements, the following can be concluded:

- GGBS concrete in slabs exhibited definite sensitivity to curing at 28 days for OPC and CEM I cements. The chloride conductivity for the various site-cured samples are within the "Excellent" durability category for both OPC and CEM I cement. The use of CEM I cement with GGBS results in a marginal increase in chloride conductivity when compared to OPC cement, also increasing the sensitivity of the concrete to curing. The use of sand curing is more beneficial than the application of curing compound, no active curing or hessian curing (in order of effectiveness) for OPC/GGBS concretes at 28 days. For the CEM I concrete at 28 days this trend is somewhat similar in that sand curing is more beneficial than hessian curing, followed by the application of a curing compound or no active curing (in order of effectiveness);

- FA concrete in slabs exhibited definite sensitivity to curing at 28 days for OPC and CEM I cements. The chloride conductivity for the various site-cured samples are within the "Excellent" and "Good" durability category for both OPC and CEM I cement. The use of CEM I cement with FA results in a noticeable reduction in chloride conductivity when compared to OPC cement, also reducing the sensitivity of the concrete to curing. The use of sand curing is more beneficial than the application of curing compound, hessian curing or no active curing (in order of effectiveness) for OPC/FA concretes at 28 days. For the CEM I concrete at 28 days this trend is somewhat similar in that sand curing is more beneficial than hessian curing, the application of curing compound or no active curing (in order of effectiveness);
- CSF concrete in slabs exhibited definite sensitivity to curing at 28 days for OPC and CEM I cements. The chloride conductivity for the various site-cured samples are within the "Good" to "Poor" durability category for OPC cements and "Excellent" to "Good" durability category for CEM I cement. The use of CEM I cement with CSF results in a noticeable reduction in chloride conductivity when compared to OPC cement (particularly for wet-cured samples) but increases the sensitivity of the concrete to curing. Hessian curing is similar to sand curing, followed by the application of curing compound or no active curing (in order of effectiveness) for OPC/GGBS concretes at 28 days. For CEM I concrete at 28 days this trend is repeated with sand and hessian curing more effective than curing compound curing and no active curing (in order of effectiveness); and
- FA concrete when used with OPC cement exhibited a marked sensitivity to curing when compared to the GGBS and CSF concretes used with OPC cement. For CEM I cement however FA concrete did not exhibit this trend and showed a similar sensitivity to curing to GGBS and CSF concretes. The GGBS and CSF concretes however showed an increase in sensitivity to curing when used with CEM I cement.

5.4.3 SLAB SERIES

5.4.3.1 120-Day Results

The data is discussed for the elements cast using OPC and CEM I separately. The slab series 1&2 were cast using OPC while series 3&4 were cast using CEM I.

5.4.3.2 Observations and Discussion: Series Cast Using OPC Cement

Figure 35 shows the 120-day chloride conductivity results for the OPC/GGBS (slab A1 and A2), OPC/FA (slab B1 and B2) and OPC/CSF (slab C1 and C2) concretes (together with environmental rating), with reference to the curing methods.

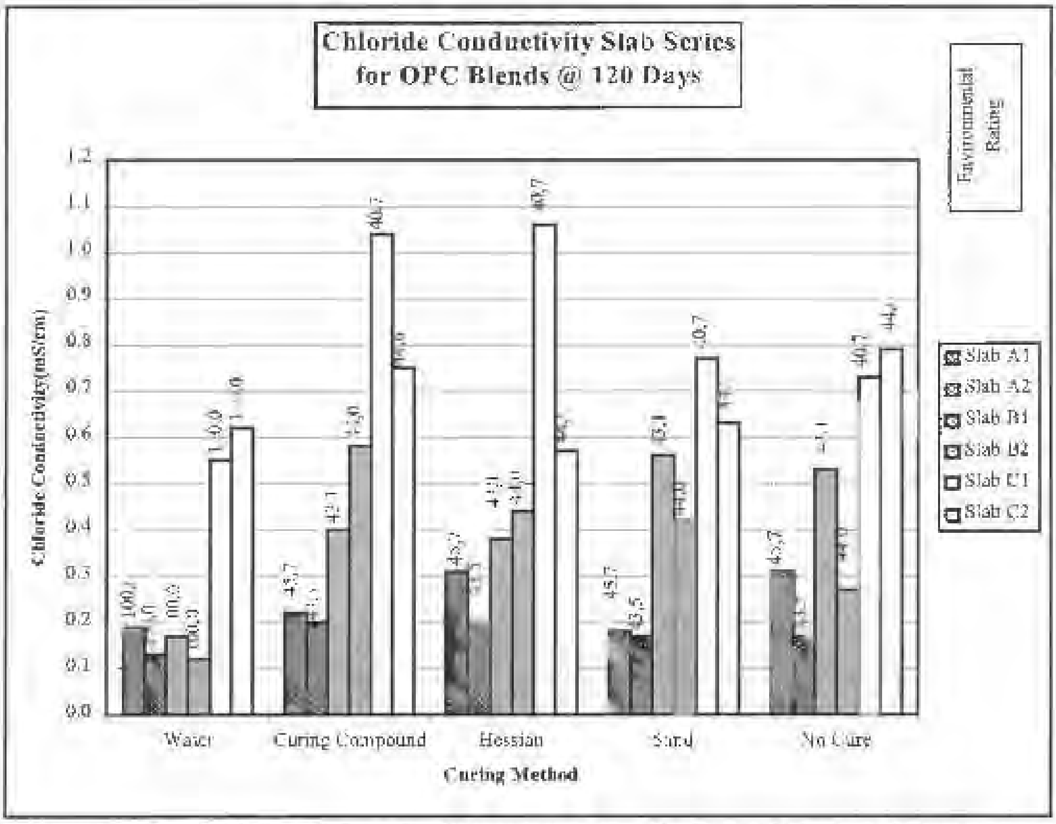


FIGURE 35: 120-DAY CHLORIDE CONDUCTIVITY RESULTS FOR OPC CONCRETES (TOGETHER WITH THE ENVIRONMENTAL RATING), PLOTTED AGAINST VARIOUS CURING METHODS.

The 120-day chloride conductivity results for the GGBS/OPC concrete are given in Table 39.

TABLE 39: 120-DAY CHLORIDE CONDUCTIVITY RESULTS FOR OPC/GGBS CONCRETE PER CURING METHOD.

CURING METHOD	CHLORIDE CONDUCTIVITY (SLAB A1 SERIES) mS/cm	CHLORIDE CONDUCTIVITY (SLAB A2 SERIES) mS/cm	MEAN CHLORIDE CONDUCTIVITY mS/cm	MEAN CURING REDUCTION RATIO
WATER	0,19	0,13	0,16	
COMPOUND	0,22	0,20	0,21	0,31
HESSIAN	0,31	0,20	0,26	0,63
SAND	0,18	0,17	0,18	0,13
UNCURED	0,31	0,17	0,24	0,50

All the results are similar and fall in a narrow band, within the "Excellent" durability category. Sand curing is the most effective site-curing method followed by the application of curing compound, no active curing and hessian curing (in order of effectiveness). Little variation is evident between the various site-cured results and they effectively yield the same durability properties in terms of chloride conductivity. Interestingly the order of efficiency of site-curing has not altered substantially when compared with the 28-day results for OPC/GGBS. The change in chloride conductivity results, relative to the 28-day results, using the

120-day results as a base, indicate that sand curing shows the largest change while no active curing the least.

The 120-day Chloride Conductivity results for the OPC/FA concrete are given in Table 40.

TABLE 40: 120-DAY CHLORIDE CONDUCTIVITY RESULTS FOR OPC/FA CONCRETE PER CURING METHOD.

CURING METHOD	CHLORIDE CONDUCTIVITY (SLAB B1 SERIES) mS/cm	CHLORIDE CONDUCTIVITY (SLAB B2 SERIES) mS/cm	MEAN CHLORIDE CONDUCTIVITY mS/cm	MEAN CURING REDUCTION RATIO
WATER	0,17	0,12	0,15	
COMPOUND	0,40	0,58	0,49	2,27
HESSIAN	0,38	0,44	0,41	1,73
SAND	0,56	0,42	0,49	2,27
UNCURED	0,53	0,27	0,40	1,67

All the results are similar and fall in a narrow band, within the "Excellent" durability category. No active curing appears to be the most effective site-curing method followed by the hessian curing, sand curing and the application of curing compound (in order of effectiveness). Little variation is evident between the various site-cured results although practically, the differences are not of great significance. Interestingly the order of efficiency of site-curing has altered when compared with the 28-day results for OPC/FA.

The change in chloride conductivity results, relative to the 28-day results, using the 120-day results as a base, indicate that all of the curing methods (including no active curing) exhibit a substantial change in chloride conductivity with time, most noticeably full water curing.

The 120-day Chloride Conductivity results for the OPC/CSF concrete are given in Table 41.

TABLE 41: 120-DAY CHLORIDE CONDUCTIVITY RESULTS FOR OPC/CSF CONCRETE PER CURING METHOD.

CURING METHOD	CHLORIDE CONDUCTIVITY (SLAB C1 SERIES) mS/cm	CHLORIDE CONDUCTIVITY (SLAB C2 SERIES) mS/cm	MEAN CHLORIDE CONDUCTIVITY mS/cm	MEAN CURING REDUCTION RATIO
WATER	0,55	0,62	0,59	
COMPOUND	1,04	0,75	1,04	0,76
HESSIAN	1,06	0,57	1,06	0,80
SAND	0,77	0,63	0,70	0,19
UNCURED	0,73	0,79	0,76	0,30

The results for hessian and curing compound curing fall in a narrow band, within the "Good" durability category, while the result for wet curing, sand curing and no active curing fall within the "Excellent" durability category. Sand curing is the most effective site-curing method followed by no active curing, the application of curing compound and hessian curing (in order of effectiveness). The results have improved markedly, when compared with the 28-day results, particularly for wet curing, sand curing and no active curing.

Figure 36 shows the mean change in 120-day chloride conductivity results for the various curing methods, and different concretes cast using OPC cement and is based on mean curing reduction ratio as presented in Tables 34 through 36.

OPC/FA concrete generally exhibited a substantially higher "curing reduction ratio" in comparison to OPC/GGBS and OPC/CSF concretes, indicating its sensitivity to curing. The OPC/FA concrete indicates that Hessian curing and no active curing are noticeably more efficient than sand curing or the application of curing compound. The OPC/GGBS concrete indicates that sand curing is more efficient than the application of curing compound, no active curing or hessian curing (in order of effectiveness). OPC/CSF concrete on the other hand indicates that sand curing and no active curing are more effective than the application of curing compound or hessian curing (in order of effectiveness).

The "curing reduction ratio" for OPC/FA concrete has reduced marginally from 1,95 - 2,80 at 28 days to 1,67 - 2,27 at 120 days, an indication of the slow improvement of durability properties with time. For OPC/GGBS concrete the "curing reduction ratio" has also increased with time from 0,19 - 0,35 at 28 days to 0,13 - 0,63 at 120 days. For OPC/CSF concrete the "curing reduction ratio" has also increased with time from 0,01 - 0,37 at 28 days to 0,19 - 0,80 at 120 days.

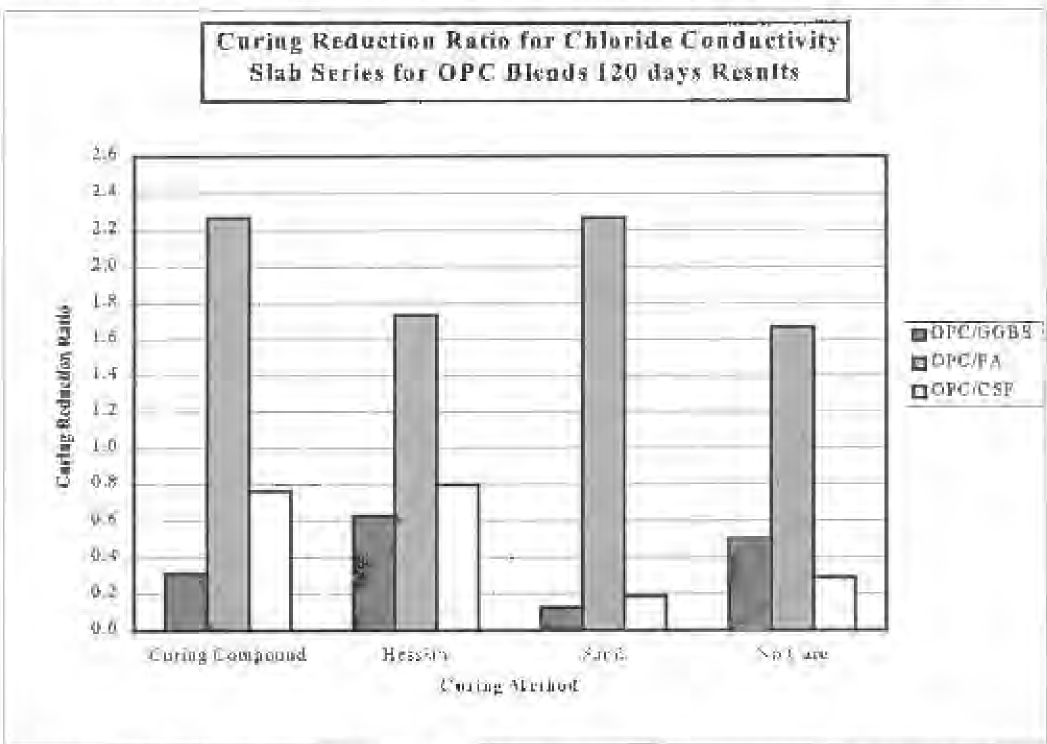


FIGURE 36: CHANGE IN 120-DAY CHLORIDE CONDUCTIVITY RESULTS FOR SLAB SERIES CAST USING OPC, PLOTTED AGAINST RESPECTIVE CURING METHOD.

5.4.3.3 Observations and Discussion: Series Cast Using CEM I Cement

Figure 37 shows the 120-day chloride conductivity results for the CEM I/GGBS (slab A3 and A4), CEM I/FA (slab B3 and B4) and CEM I/CSF (slab C3 and C4) concretes (together with environmental rating), with reference to the curing methods.

The 120-day chloride conductivity results for the CEM I/GGBS concrete are given in Table 42.

TABLE 42: 120-DAY CHLORIDE CONDUCTIVITY RESULTS FOR CEM I/GGBS CONCRETE PER CURING METHOD.

CURING METHOD	CHLORIDE CONDUCTIVITY (SLAB A3 SERIES) mS/cm	CHLORIDE CONDUCTIVITY (SLAB A4 SERIES) mS/cm	MEAN CHLORIDE CONDUCTIVITY mS/cm	MEAN CURING REDUCTION RATIO
WATER	0,25	0,26	0,26	
COMPOUND	0,37	0,37	0,37	0,69
HESSIAN	0,30	0,33	0,31	0,19
SAND	0,35	0,34	0,34	0,31
UNCURED	0,47	0,41	0,44	0,69

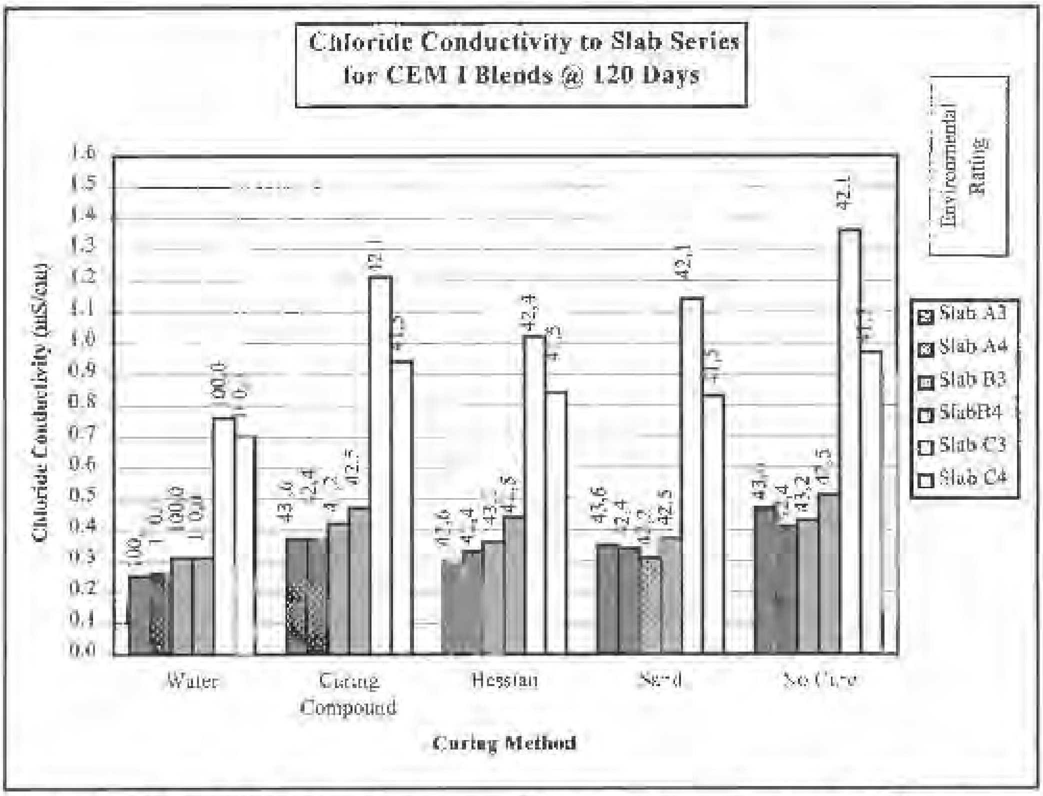


FIGURE 37: 120-DAY CHLORIDE CONDUCTIVITY RESULTS FOR CEM I CONCRETES (TOGETHER WITH THE ENVIRONMENTAL RATING), PLOTTED AGAINST VARIOUS CURING METHODS.

The results are similar and fall in a narrow band, within the "Excellent" durability category. Hessian curing is the most effective site-curing method followed by sand curing, the application of curing compound and no active curing (in order of effectiveness). Little variation is evident between the various site-cured results and they effectively yield the same durability properties in terms of chloride conductivity. Interestingly the order of efficiency of site-curing has not altered substantially when compared with the 28-day results for CEM I/GGBS. The change in chloride conductivity results, relative to the 28-day results, using the 120-day results as a base, indicate that curing compound curing shows the largest change while sand curing the least, not consistent with the OPC/GGBS concrete results. When these results are compared to the OPC concrete results i.e. slab A1 and A2, at the same element age, it is noted that generally for CEM I concrete all the curing methods produced consistently higher conductivity results.

The 120-day chloride conductivity results for the CEM I/FA concrete are given in Table 43.

TABLE 43: 120-DAY CHLORIDE CONDUCTIVITY RESULTS FOR CEM I/FA CONCRETE PER CURING METHOD.

CURING METHOD	CHLORIDE CONDUCTIVITY (SLAB B3 SERIES) mS/cm	CHLORIDE CONDUCTIVITY (SLAB B4 SERIES) mS/cm	MEAN CHLORIDE CONDUCTIVITY mS/cm	MEAN CURING REDUCTION RATIO
WATER	0,31	0,31	0,31	
COMPOUND	0,42	0,47	0,45	0,52
HESSIAN	0,36	0,44	0,40	0,29
SAND	0,31	0,37	0,34	0,10
UNCURED	0,43	0,51	0,47	0,52

The results are similar and fall in a narrow band, within the "Excellent" durability category. Sand curing is the most effective site-curing method followed by hessian curing, the application of curing compound and no active curing (in order of effectiveness). Little variation is evident between the various site-cured results and they effectively yield the same durability properties in terms of chloride conductivity. Interestingly the order of efficiency of site-curing has not altered when compared with the 28-day results for CEM I/FA.

The change in chloride conductivity results, relative to the 28-day results, using the 120-day results as a base, indicates that sand curing shows the largest change while curing compound curing the least. Also the average change is slightly less than for OPC/FA concrete.

When these results are compared to the OPC cement results i.e. slab B1 and B2, at the same element age it is noted that generally for CEM I concrete all the site-curing methods produce marginally lower conductivity, while full water-curing produces substantially higher chloride conductivity results.

The 120-day chloride conductivity results for the CEM I/CSF concrete are given in Table 44.

TABLE 44: 120-DAY CHLORIDE CONDUCTIVITY RESULTS FOR CEM I/CSF CONCRETE PER CURING METHOD.

CURING METHOD	CHLORIDE CONDUCTIVITY (SLAB C3 SERIES) mS/cm	CHLORIDE CONDUCTIVITY (SLAB C4 SERIES) mS/cm	MEAN CHLORIDE CONDUCTIVITY mS/cm	MEAN CURING REDUCTION RATIO
WATER	0,76	0,70	0,73	
COMPOUND	1,21	0,94	1,08	0,47
HESSIAN	1,02	0,84	0,93	0,27
SAND	1,14	0,83	0,99	0,35
UNCURED	1,36	0,97	1,17	0,60

All the site-cured results are fairly similar and fall in a narrow band, within the "Good" durability category, while the wet cured result is within the "Excellent" durability category. Hessian curing is the most effective site-curing method followed by sand curing, the application of curing compound and no active curing (in order of effectiveness). Little variation is evident between the various site-cured results and they effectively yield the same durability properties in terms of chloride conductivity. Interestingly the order of efficiency of site-curing has not altered substantially when compared with the 28-day results for CEM I/CSF. The change in chloride conductivity results, relative to the 28-day results, using the 120-day results as a base, indicates that sand curing shows the largest change while curing compound curing the least.

When these results are compared to the OPC cement results i.e. slab C1 and C2, at the same element age, it is noted that generally for CEM I concrete for wet curing, sand curing and no active curing the conductivity is marginally higher. For curing compound and hessian curing the conductivity is marginally lower.

Figure 38 shows the change in 120-day chloride conductivity for the various curing methods, and different concretes cast using CEM I cement and is based on mean curing reduction ratio as presented in Tables 37 through 39.

In this case all the concretes exhibit a reasonably similar range of "curing reduction ratios". The only deviation from this is the marked effectiveness of sand curing exhibited for CEM I/FA concretes.

CEM I/GGBS concrete indicates that hessian curing is marginally more effective than sand curing, followed by the application of curing compound and no active curing (in order of effectiveness). CEM I/FA on the other hand indicates that sand curing is markedly more effective than hessian curing and both are noticeably more efficient that the application of curing compound and no active curing, shown to be the most ineffective. CEM I/CSF indicates that hessian and sand curing have virtually the same effect, followed by the application of curing compound and no active curing (in order of effectiveness).

All three concretes exhibit consistency in that sand and hessian curing exhibit a marked beneficial effect of curing with curing compound and no active curing exhibiting a far less beneficial effect.

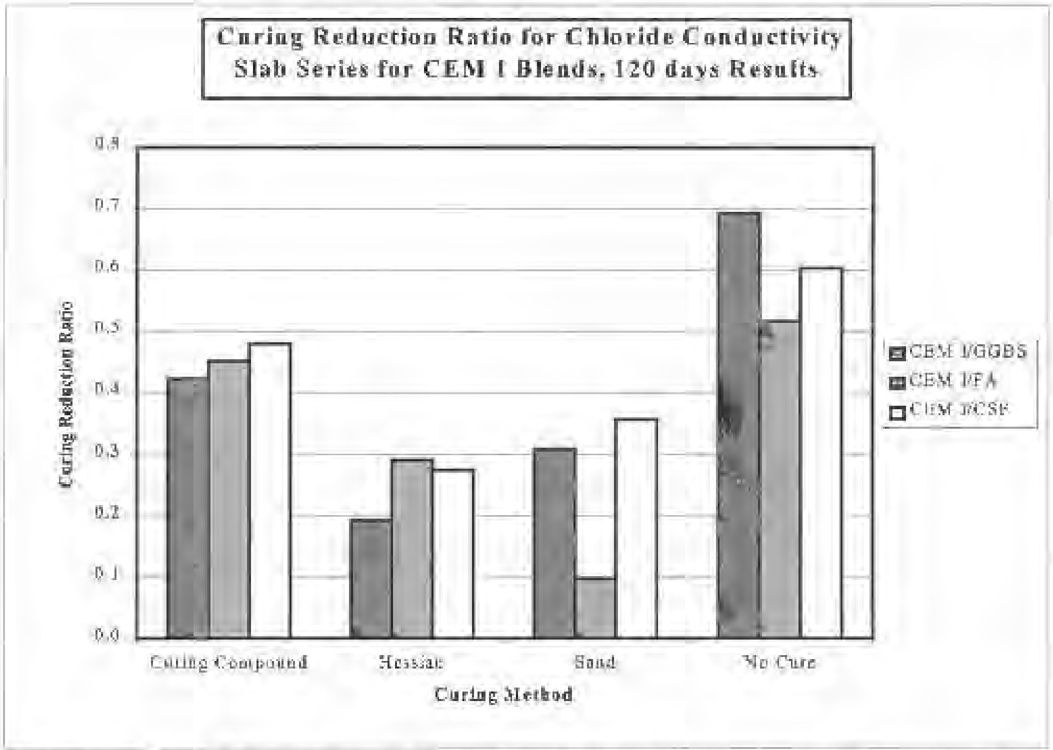


FIGURE 38: CHANGE IN 120-DAY CHLORIDE CONDUCTIVITY RESULTS FOR SLAB SERIES CAST USING CEM I, PLOTTED AGAINST RESPECTIVE CURING METHOD.

Interestingly the ratio for CEM I/FA concrete has remained relatively unchanged from 0,35 - 0,75 at 28 days to 0,10 - 0,52 at 120 days. CEM I/CSF concrete exhibited a reduction in ratio from approximately 0,51 - 1,05 at 28 days to 0,27 - 0,60 at 120 days. For CEM I/GGBS concrete the ratio has reduced with time from 0,10 - 0,83 at 28 days to 0,19 - 0,69 at 120 days.

5.4.3.4 Conclusions Relating to 120-Day Results

Based on the observation and discussion and subject to the environmental conditions experienced by the elements, the following can be concluded:

- GGBS concrete in slabs exhibited definite sensitivity to curing at 120 days when used with OPC and CEM I cements. The chloride conductivity for the various site-cured samples are within the "Excellent" durability category for both OPC and CEM I cement. The use of CEM I cement with GGBS results in a noticeable increase in chloride conductivity when compared to OPC cement. The use of sand curing is more beneficial than the application of curing compound, hessian curing or no active curing (in order of effectiveness) for OPC/GGBS concretes at 120 days. For the CEM I concrete at 120 days this trend is similar in that hessian curing is more beneficial than sand curing, the application of a curing compound or no active curing (in order of effectiveness). In terms of change in chloride conductivity with time, the OPC and CEM I cements exhibit a similar reduction in chloride conductivity with element age. The reduction does not follow any set trend and variability is evident between the two data sets;
- FA concrete in slabs exhibited definite sensitivity to curing at 120 days for OPC and CEM I cements. The chloride conductivity for the various site-

cured samples are within the "Excellent" and durability category for both OPC and CEM I cement. The use of CEM I cement with FA results in an increase in chloride conductivity for full wet curing and a noticeable reduction for the site-curing, when compared to OPC cement. No active curing is more beneficial than hessian curing, sand curing or the application of curing compound (in order of effectiveness) for OPC/FA concretes at 120 days. For the CEM I concrete at 120 days this trend is not repeated in that sand curing is more beneficial than hessian curing, the application of curing compound or no active curing (in order of effectiveness). In terms of change in chloride conductivity with time, the CEM I cements exhibit a less pronounced reduction in chloride conductivity with element age, in comparison with the OPC cement. FA concrete exhibits the largest reduction in chloride conductivity with age of the three concrete types. The reduction does not follow any set trend and variability is evident between the two data sets;

- CSF concrete in slabs exhibited definite sensitivity to curing at 120 days for OPC and CEM I cements. The chloride conductivity for the various site-cured samples are within the "Excellent" to "Good" durability category for OPC and CEM I cements. The use of CEM I cement with CSF results in a marginal increase in chloride conductivity when compared to OPC cement. The use of sand curing is more beneficial than no active curing, the application of curing compound or hessian curing (in order of effectiveness) for OPC/CSF concretes at 120 days. For the CEM I concrete at 120 days this trend is not repeated in that sand curing is more beneficial than hessian curing, the application of curing compound or no active curing (in order of effectiveness). In terms of change in chloride conductivity with time, the CEM I/CSF cement exhibit a less pronounced reduction in chloride conductivity with element age, in comparison with the CEM I/FA concrete and a similar reduction to CEM I/GGBS concrete. The absence of a data set for OPC/FA at 28 days makes the reduction to 120 days impossible to assess; and
- FA concrete when used with OPC cement exhibited a more marked sensitivity to curing at 120 days when compared to the GGBS and CSF concrete used with OPC cement. For CEM I cement however FA concrete did not exhibit this trend and showed similar sensitivity to curing as for CSF concretes when used with CEM I cement. However GGBS concrete when used with CEM I cement, exhibited a marginal increase in sensitivity to curing at 120 days.

5.4.3.5 General Conclusions Relating to Site-Cured Slab Samples

Based on the observations and discussion in the proceeding section of this chapter the following can be concluded, relative to site-cured slab samples, and are considered as the key findings for this chapter:

- GGBS concrete in slabs exhibited definite sensitivity to curing at both 28 days and 120 days when used with both OPC and CEM I cements, however this was more evident for CEM I cement at both 28 and 120 days. At both 28 and 120 days the chloride conductivity for various site-cured samples are within the "Excellent" durability category for both OPC and CEM I cements. CEM I cement had the effect of increasing the chloride conductivity results at both 28 and 120-day element ages in comparison with OPC cement. Regarding the site-curing methods, the use of sand curing is more beneficial than the application of curing compound and no active curing (in order of effectiveness) at both 28 and 120 days for both the OPC and CEM I cements. The change in cement type appears to have no influence on the reduction of the chloride conductivity with time;

- FA concrete in slabs exhibited definite sensitivity to curing at both 28 days and 120 days when used with both OPC and CEM I cements, however this was more evident for OPC cement at both 28 and 120 days. At both 28 and 120 days the chloride conductivity for various site-cured samples are within the "Excellent" durability category for both OPC and CEM I cements. OPC cement had the effect of increasing the chloride conductivity results at both 28 and 120-day element ages in comparison with CEM I cement. Generally the use of sand curing is more beneficial than hessian curing and the application of curing compound and no active curing (in order of effectiveness) at both 28 and 120 days for both the OPC and CEM I cements. The change in cement type appears to influence the change in chloride conductivity with time, in that CEM I cement exhibited a less pronounced reduction in chloride conductivity in comparison to OPC cement. FA concrete exhibited by the far the largest reduction in chloride conductivity with time of the three concrete types; and
- CSF concrete in slabs exhibited definite sensitivity to curing at both 28 days and 120 days when used with both OPC and CEM I cements, possibly marginally more evident for OPC cement at 120 days (no data at 28 days for CSF concrete). At 120 days the chloride conductivity for various site-cured samples are within the "Good" to "Excellent" durability category for both OPC and CEM I cements. CEM I cement had the effect of marginally increasing the chloride conductivity results at 120-day element ages in comparison with OPC cement. Sand curing is generally more beneficial than curing compound curing and no active curing (in order of effectiveness) at 28 and 120 days for OPC cement. The change in cement type appears to have no influence on the reduction of the chloride conductivity with time.

5.4.3.6 General Summary Relating to Site-Cured Samples (Walls and Slabs)

Table 45 represents a summary of all the data used in the this chapter and can be considered to be a summary of findings

TABLE 45: GENERAL SUMMARY OF CHLORIDE CONDUCTIVITY RESULTS FOR ALL CONCRETE TYPES AND VARIOUS CURING REGIMES.

		OPC CEMENT				CEM I CEMENT	
		WALL SERIES		SLAB SERIES		SLAB SERIES	
		28 DAYS	120 DAYS	28 DAYS	120 DAYS	28 DAYS	120 DAYS
GGBS BINDER	CURING * SENSITIVITY	0,6 to 1,7	0,6 to 1,0	0,2 to 0,5	0,1 to 0,6	1,1 to 1,2	0,2 to 0,7
GGBS BINDER	CHLORIDE COND. RESULTS (mS/cm)	0,33 to 0,88 Water (0,33) Formwork (0,52) Hessian (0,57) Uncured (0,61) C. Comp. (0,88)	0,24 to 0,49 Water (0,24) Hessian (0,33) Formwork (0,32) C. Comp. (0,39) Uncured (0,49)	0,25 to 0,38 Water (0,25) Sand (0,31) C. Comp. (0,35) Uncured (0,35) Hessian (0,38)	0,16 to 0,26 Water (0,16) Sand (0,18) C. Comp. (0,21) Uncured (0,24) Hessian (0,26)	0,29 to 0,65 Water (0,29) Sand (0,32) Hessian (0,41) C. Comp. (0,62) Uncured (0,65)	0,26 to 0,44 Water (0,26) Hessian (0,31) Sand (0,34) C. Comp. (0,37) Uncured (0,44)
GGBS BINDER	CHANGE IN RESULTS WITH TIME		30% to 130% reduction		10% to 70% reduction		10% to 70% reduction
FA BINDER	CURING * SENSITIVITY	No data	2,7 to 3,3	2,0 to 2,8	1,7 to 2,3	0,1 to 0,5	0,1 to 0,5
FA BINDER	CHLORIDE COND. RESULTS (mS/cm)	No data	0,17 to 0,73 Water (0,17) Hessian (0,63) Formwork (0,67) C. Comp. (0,71) Uncured (0,73)	0,42 to 1,60 Water (0,42) Sand (1,24) C. Comp. (1,26) Hessian (1,34) Uncured (1,60)	0,15 to 0,49 Water (0,15) Hessian (0,41) Sand (0,49) Uncured (0,40) C. Comp. (0,49)	0,55 to 0,80 Water (0,55) C. Comp. (0,59) Sand (0,74) Hessian (0,77) Uncured (0,80)	0,31 to 0,47 Water (0,31) Sand (0,34) Hessian (0,40) C. Comp. (0,45) Uncured (0,47)
FA BINDER	CHANGE IN RESULTS WITH TIME		No data		90% to 180% reduction		30% to 120% reduction

TABLE 45: GENERAL SUMMARY OF CHLORIDE CONDUCTIVITY RESULTS FOR ALL CONCRETE TYPES AND VARIOUS CURING REGIMES. (CONT.)

		OPC CEMENT				**CEM I CEMENT**	
		WALL SERIES		**SLAB SERIES**		**SLAB SERIES**	
		28 DAYS	**120 DAYS**	**28 DAYS**	**120 DAYS**	**28 DAYS**	**120 DAYS**
CSF BINDER	**CURING * SENSITIVITY**	No data	0,1 to 0,3	0,1 to 0,4	0,2 to 1,2	0,5 to 1,1	0,3 to 0,6
	CHLORIDE COND. RESULTS (mS/cm)	No data	0,79 to 1,00 Water (0,79) Formwork (0,90) C. Comp. (0,97) Hessian (1,00) Uncured (1,00)	0,1 to 0,4 Water (1,56) Hessian (1,58) Sand (1,60) C. Comp. (1,85) Uncured (2,14)	0,59 to 1,04 Water (0,59) Sand (0,70) Uncured (0,76) Hessian (1,06) C. Comp. (1,04)	0,64 to 1,31 Water (0,64) Sand (0,94) Hessian (0,97) C. Comp. (1,10) Uncured (1,31)	0,73 to 1,17 Water (0,73) Hessian (0,93) Sand (0,99) C. Comp. (1,08) Uncured (1,17)
	CHANGE IN RESULTS WITH TIME		No data		No data		5% to 50% reduction

* Note : The curing sensitivity is indicated by the "curing reduction ratio".

CHAPTER 6

WATER SORPTIVITY RESULTS

6.1 INFLUENCE OF WATER/BINDER RATIO

6.1.1 WATER SORPTIVITY RESULTS AT 28 DAYS

Table 46 shows the water/binder ratios that were used to achieve a characteristic compressive strength of 30 MPa for the wall series and 35 MPa for the slab series, for the three concrete types.

TABLE 46: WATER/BINDER RATIOS FOR WALL AND SLAB ELEMENTS.

BINDER TYPE	WATER/BINDER RATIO	
	WALL SERIES	SLAB SERIES
CEMENT/GGBS	0,50	0,46
CEMENT/FA	0,50	0,47
CEMENT/CSF	0,57	0,54

Figure 39 shows the water sorptivity results for 28-day wet-cured cubes plotted against the respective water/binder ratio, for the three binder types.

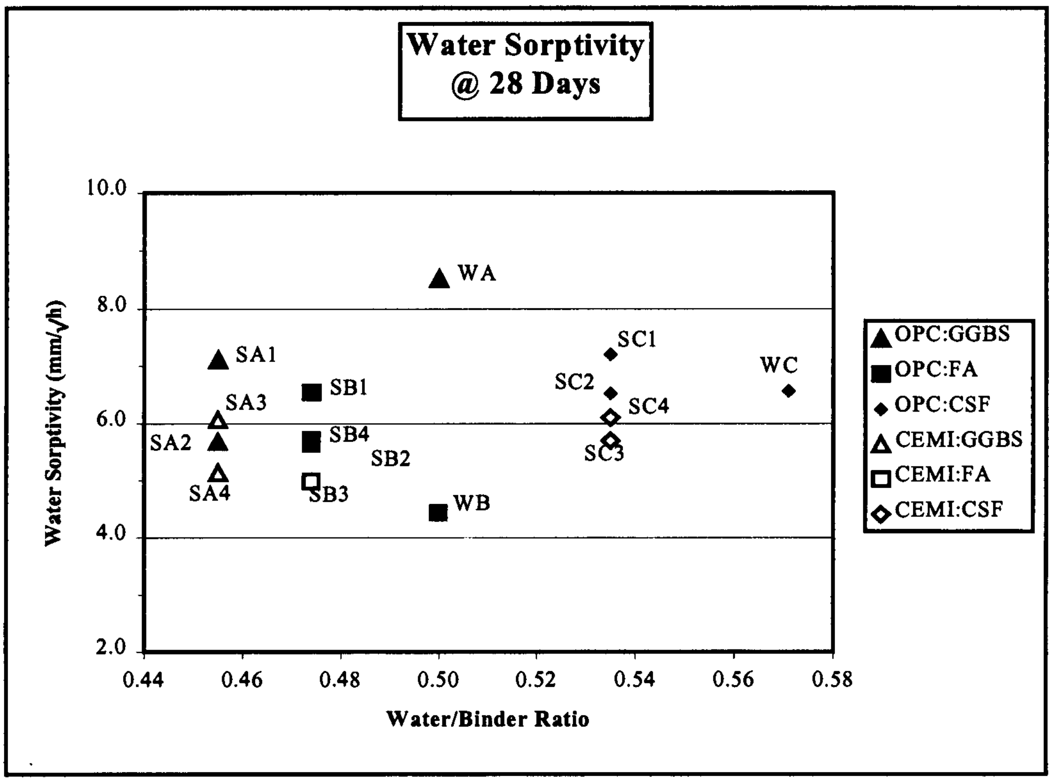


FIGURE 39: WATER SORPTIVITY RESULTS FOR 28 DAYS WET-CURED CUBES PLOTTED AGAINST WATER/BINDER RATIO.

For all the concrete types, a group of results related to the change in cement manufacture specification is evident. Slab 3&4 series (based on CEM I cement) are grouped together and so too are slabs 1&2 series (based on OPC cement).

Although the shift is small (1,0 mm/√h), CEM I cement has the effect of slightly reducing (i.e. improving) the water sorptivity.

For the slab series the OPC/GGBS concrete yields water sorptivity results in the range of 5,7 mm/√h to 7,2 mm/√h. The OPC/FA concrete yield results in the range of 5,6 mm/√h to 6,5 mm/√h and the OPC/CSF concrete in the range of 6,5 mm/√h to 7,2 mm/√h. The OPC/GGBS and OPC/CSF concretes yields a similar range of results while the results for the OPC/FA concrete are marginally improved (lower).

For the slab series the CEM I/GGBS concrete yields water sorptivity results in the range of 5,1 mm/√h to 6,1 mm/√h. The CEM I/FA concrete yields results in the range of 5,0 mm/√h to 5,7 mm/√h and the CEM I/CSF concrete in the range of 5,7 mm/√h to 6,1 mm/√h. The CEM I/GGBS and CEM I/CSF concretes yield a similar range of results while the results for the CEM I/FA concrete are marginally improved (lower).

For the wall series the OPC/GGBS concrete yields a water sorptivity of 8,5 mm/√h, the OPC/FA concrete a water sorptivity of 4,4 mm/√h and the OPC/CSF concrete a water sorptivity of 6,6 mm/√h. When compared to the results for the slab series the result for the OPC/FA concrete appears to be somewhat low and the result for the OPC/GGBS concrete somewhat high.

As a general characterisation[33], water sorptivity below 6,0 mm/√h is considered to provide "Excellent" durability properties, above 6,0 mm/√h and below 10,0 mm/√h is considered "Good" and above 10,0 mm/√h is considered "Poor". All of the results satisfy or exceed the "Good" durability category, with the lower limit of the data set well inside the "Excellent" durability category.

When comparing the above data with currently available water sorptivity data, from the Western Cape[18], for 28-day wet-cured samples, it was noted that the all the concretes exhibited very similar results. This confirms the sensitivity of the water sorptivity index to curing practices or regime rather than material selection.

6.1.2 WATER SORPTIVITY RESULTS AT 120 DAYS

Figure 40 shows the water sorptivity results for 120-day wet-cured cubes, plotted against the respective water/binder ratio, for the three concrete types.

Any trend evident at 28 days has been erased at 120 days and the data exhibits a general spread rather than any grouping. Notwithstanding this the water sorptivity results have generally reduced, which indicates an improvement in water sorptivity with further curing as may be expected.

For the slab series the OPC/GGBS concrete yields water sorptivity results in the range of 4,0 mm/√h to 6,3 mm/√h. The OPC/FA concrete yields results in the range of 3,7 mm/√h to 5,0 mm/√h and the OPC/CSF concrete a value of 6,1 mm/√h. The OPC/GGBS and OPC/FA concretes yield a similar range of results while the results for the OPC/CSF concretes is marginally less favourable (higher).

For the wall series the OPC/GGBS concrete yields a water sorptivity of 5,0 mm/√h, the OPC/FA concrete a water sorptivity of 3,8 mm/√h and the OPC/CSF concrete a water sorptivity of 5,0 mm/√h.

Once again all of the results satisfy or exceed the "Good" durability category, with the lower limit of the data set well inside the "Excellent" durability category.

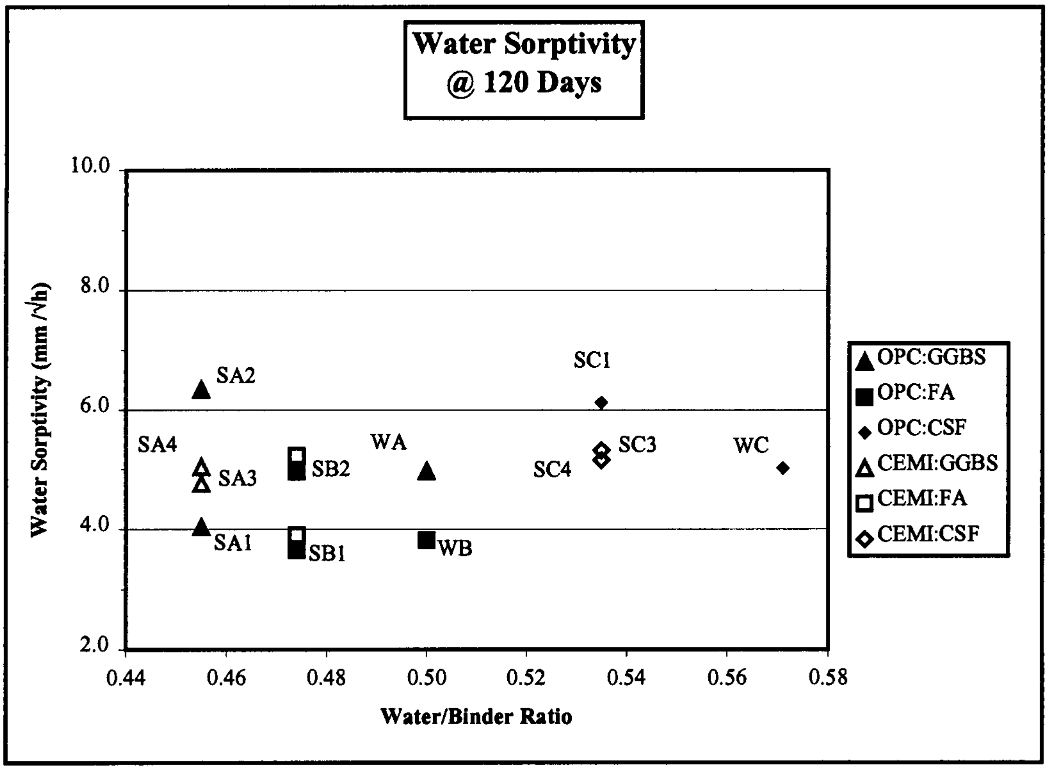


FIGURE 40: WATER SORPTIVITY RESULTS FOR 120 DAYS WET-CURED CUBES, PLOTTED AGAINST WATER/BINDER RATIO.

6.1.3 CONCLUSIONS RELATING TO THE INFLUENCE OF WATER/BINDER RATIO

Based on the observations and discussion, the following can be concluded:

- To achieve a specified compressive strength the water/binder ratio can be increased by the use of CSF as a cement extender;
- The FA concretes exhibit marginally lower results of water sorptivity at 28 and 120 days when compared with GGBS and CSF concretes, however the variation in water sorptivity between the three binder types is small;
- The use of CEM I cement resulted in slightly lower water sorptivity at 28 days, when compared with OPC cement; however at 120 days this trend was not sustained; and

6.2 INFLUENCE OF BINDER TYPE

6.2.1 WATER SORPTIVITY RESULTS AT 28 DAYS

Figure 41 shows the water sorptivity results for 28-day wet-cured cubes, plotted against the respective core compressive strengths for the three binder types.

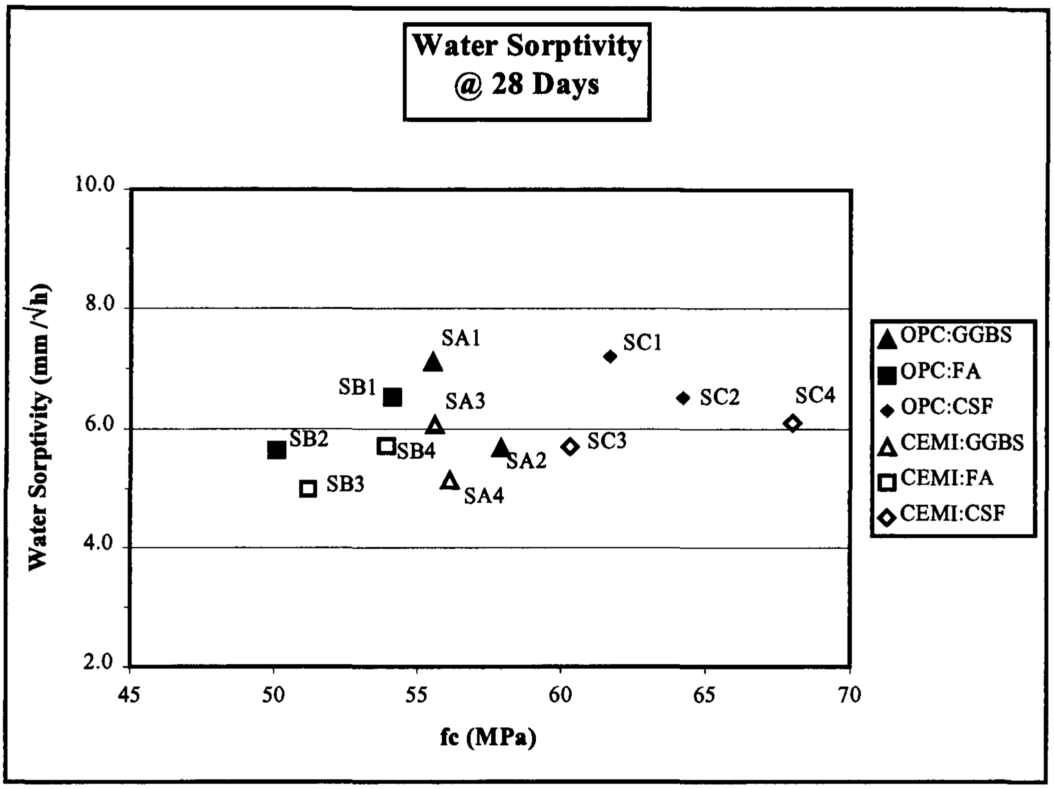


FIGURE 41: WATER SORPTIVITY RESULTS FOR 28 DAYS WET-CURED CUBES, PLOTTED AGAINST 28-DAY COMPRESSIVE CORE STRENGTHS.

In general the CEM I cement concretes show marginally improved (i.e. lower) water sorptivity results when compared to the OPC cement concretes. All of the CEM I cement concrete results are within the "Excellent" durability category, while the OPC cement concrete results are within the "Good" durability category. The range in water sorptivity results is very low over the range in compressive strengths considered, indicating that well cured concretes exhibit relatively low water sorptivities. The influence of binder type is not very pronounced in this case.

6.2.2 WATER SORPTIVITY RESULTS AT 120 DAYS

Figure 42 shows the water sorptivity results for 120-day wet-cured cubes, plotted against the respective core compressive strengths for the three binder types.

In comparison with Figure 34, the range of water sorptivity results has reduced and lies in a lower band inside the "Excellent" durability category. The CEM I and OPC cement concrete results are essentially indistinguishable, and the water sorptivity is unaffected by the strength of concrete over the range considered.

6.2.3 CONCLUSIONS RELATING TO THE INFLUENCE OF BINDER TYPE

Based on the observations and discussion the following can be concluded with regard to wet-cured cubes:

- The 28-day water sorptivity results are "indistinguishable" within the "Good" durability category; possibly it could be noted that the FA concrete yields marginally lower water sorptivity results;

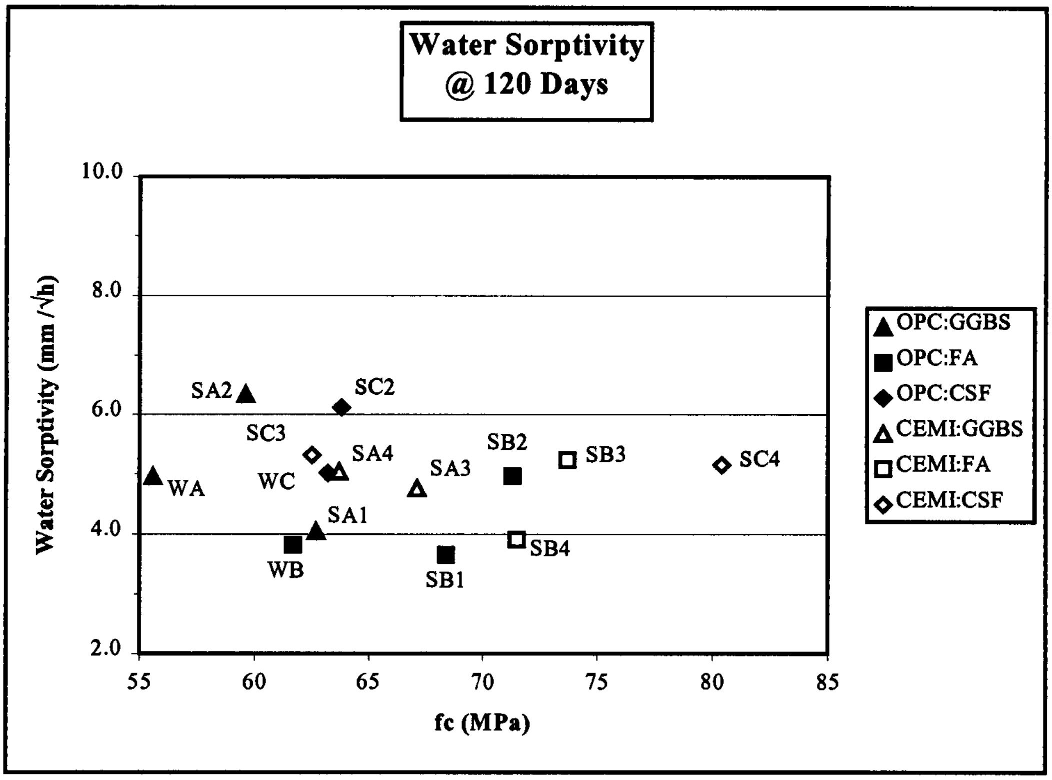


FIGURE 42: WATER SORPTIVITY RESULTS FOR 120 DAYS WET-CURED CUBES, PLOTTED AGAINST 120-DAY COMPRESSIVE CORE STRENGTHS.

- At 120 days the water sorptivity results are generally "indistinguishable" within the "Excellent" durability category. However, FA concrete yields marginally lower water sorptivity results;
- While CEM I cement exhibited marginally lower water sorptivity results than OPC cement at 28 days, this was not repeated at 120 days. The water sorptivity results at 120 days exhibit no grouping per cement type; and
- When the concrete is well-cured, such as in this case (wet-curing for 120 days) binder type has little effect over the range of concrete strengths assessed.

6.3 INFLUENCE OF ELEMENT AGE

6.3.1 GGBS CONCRETES

Table 47 shows the change in water sorptivity with time for wet-cured cubes.

TABLE 47: WATER SORPTIVITY RESULTS AT 28 AND 120 DAYS, FOR SLAB A SERIES.

ELEMENT	WATER SORPTIVITY @ 28 DAYS (mm/√h)	WATER SORPTIVITY @ 120 DAYS (mm/√h)
SLAB A1	7,2	4,0
SLAB A2	5,7	6,3
SLAB A3	6,1	4,8
SLAB A4	5,1	5,0

Figure 43 shows the 28-day and 120-day water sorptivity results for wet-cured cubes, plotted against the respective core compressive strengths for GGBS concretes.

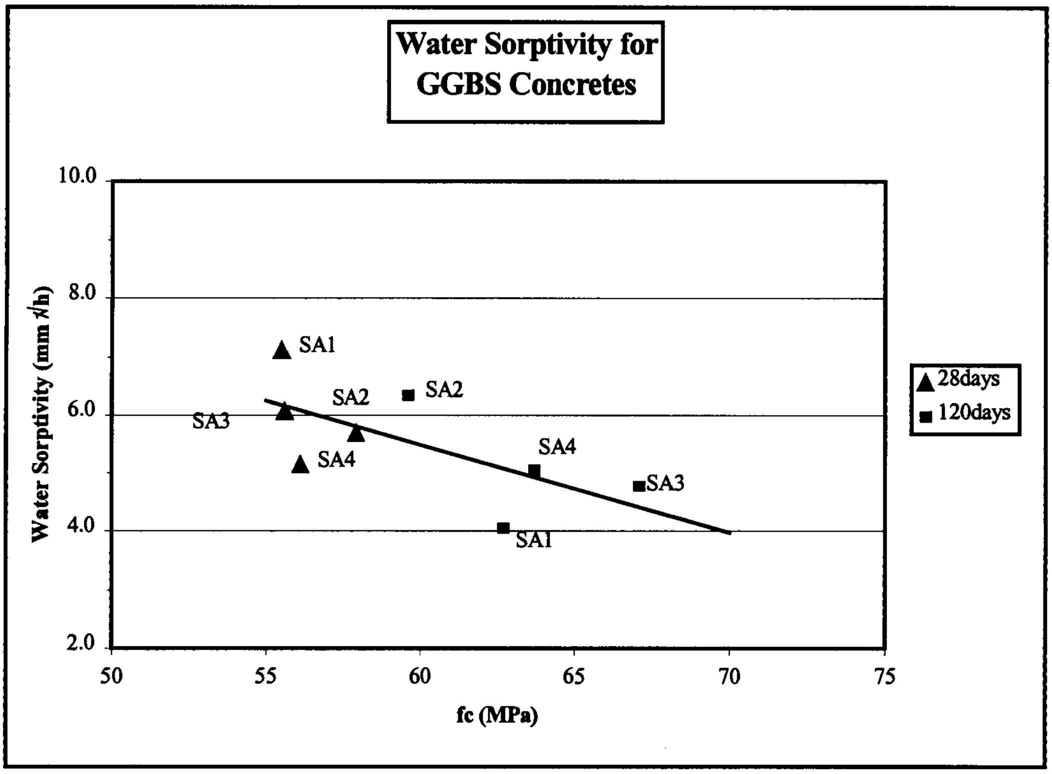


FIGURE 43: WATER SORPTIVITY RESULTS FOR GGBS CONCRETES AT 28 & 120 DAYS PLOTTED AGAINST RESPECTIVE COMPRESSIVE CORE STRENGTHS FOR WET-CURED CUBES.

Despite the scatter in the results, there is a marked trend of water sorptivity reducing with increasing strength. In effect the water sorptivity reduces with age, since the compressive strength increases with age, under wet-cured conditions.

6.3.2 FA CONCRETES

Table 48 shows the change in water sorptivity with time for wet-cured cubes.

TABLE 48: WATER SORPTIVITY RESULTS AT 28 AND 120 DAYS, FOR SLAB B SERIES.

ELEMENT	WATER SORPTIVITY @ 28 DAYS (mm/√h)	WATER SORPTIVITY @ 120 DAYS (mm/√h)
SLAB B1	6,5	3,7
SLAB B2	5,6	5,0
SLAB B3	5,0	5,2
SLAB B4	5,7	3,9

Figure 44 shows the 28-day and 120-day water sorptivity results for wet-cured cubes, plotted against the respective core compressive strengths for FA concretes.

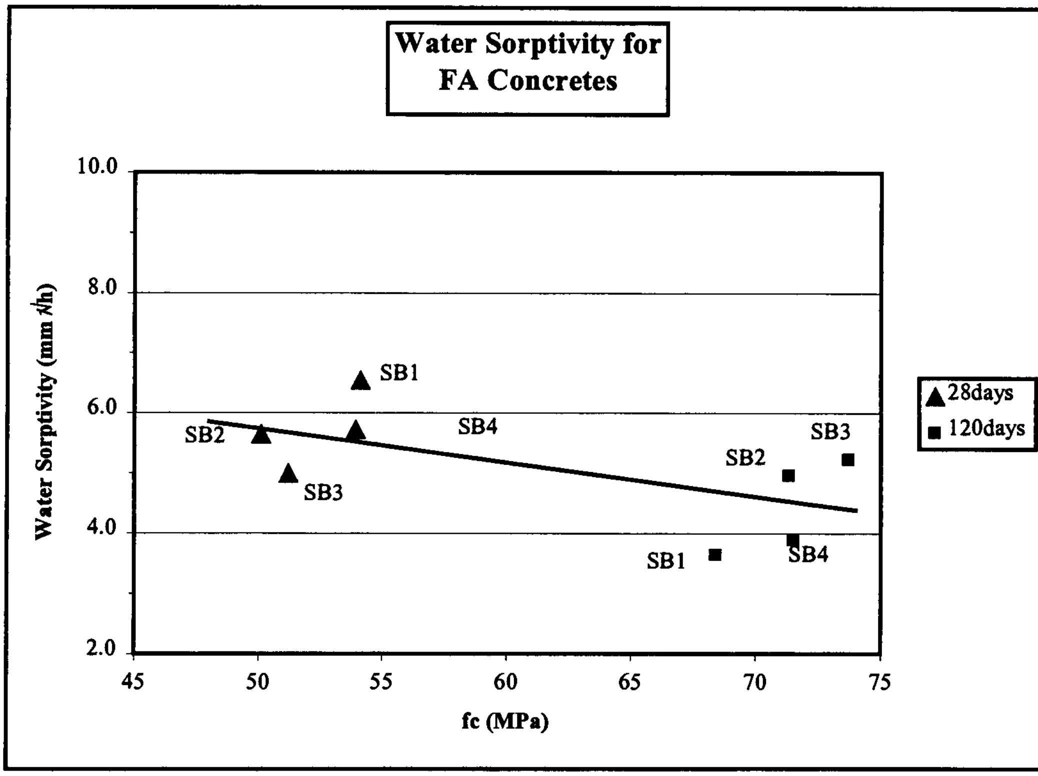


FIGURE 44: WATER SORPTIVITY RESULTS FOR FA CONCRETES AT 28 & 120 DAYS PLOTTED AGAINST RESPECTIVE COMPRESSIVE CORE STRENGTHS FOR WET-CURED CUBES.

Given the degree of scatter in the results, there is a trend of water sorptivity reducing with age. In effect the water sorptivity reduces with increasing compressive strength, since the compressive strength increases with age. In comparison to the GGBS and CSF concretes a much larger increase in compressive strength is evident. GGBS concretes exhibited an increase of approximately 10 MPa, CSF concretes remained effectively unchanged while FA concretes exhibited an increase in excess of approximately 20 MPa, over a period from 28 days to 120 days.

6.3.3 CSF CONCRETES

Table 49 shows the change in water sorptivity with time for wet-cured cubes.

TABLE 49: WATER SORPTIVITY RESULTS AT 28 AND 120 DAYS, FOR SLAB C SERIES.

ELEMENT	WATER SORPTIVITY @ 28 DAYS (mm/√h)	WATER SORPTIVITY @ 120 DAYS (mm/√h)
SLAB C1	7,2	No data
SLAB C2	6,5	6,1
SLAB C3	5,7	5,3
SLAB C4	6,1	5,2

Figure 45 shows the 28-day and 120-day water sorptivity results for wet-cured cubes, plotted against the respective core compressive strengths for CSF concretes.

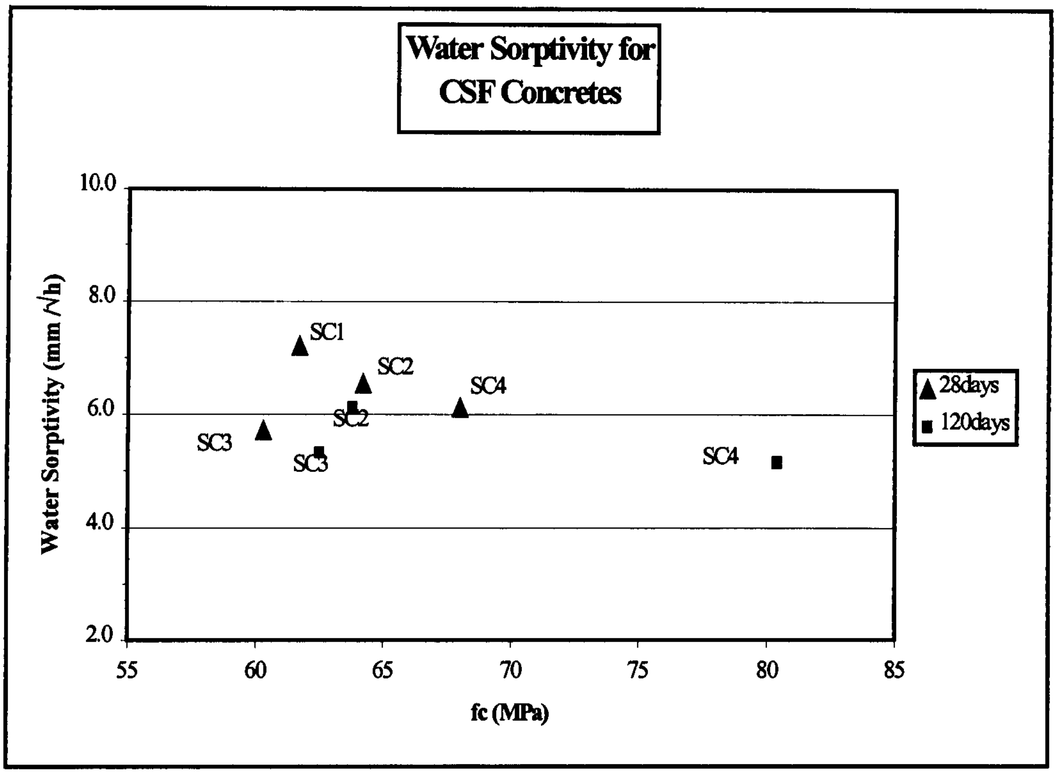


FIGURE 45: WATER SORPTIVITY RESULTS FOR CSF CONCRETES AT 28 & 120 DAYS PLOTTED AGAINST RESPECTIVE COMPRESSIVE CORE STRENGTHS FOR WET-CURED CUBES.

Given the limited results, it appears that the water sorptivity does not change appreciably with time from 28 days to 120 days - an observation that also holds true for compressive strength. The use of CSF induces more rapid hydration in the first 28 days with little change thereafter. The result for slab C4 at 120 days appears to somewhat of an outlier in that the compressive strength at 120 days has increased substantially from that at 28 days.

6.3.4 CONCLUSIONS RELATING TO THE INFLUENCE OF ELEMENT AGE

Based on the observations and discussion the following can be concluded:

- The FA and GGBS concretes show a definite trend of water sorptivity reducing with age, (in both cases from about 6,0 mm/√h to 4,0 mm/√h). Results for the individual elements exhibited scatter, but the general trend is well established. Compressive strength also increased substantially with time for FA and GGBS concretes, over the period 28 days to 120 days;
- The results for the CSF concretes exhibit very little change with time, for either water sorptivity or compressive strength; and

6.3.5 GENERAL CONCLUSIONS RELATING TO FULLY WATER CURED SAMPLES

Based on the observations and discussion in the preceding three sections of this chapter the following can be concluded, relative to wet-cured samples, and considered as the key findings for the first section of this chapter:

- The FA concrete produces marginally the lowest water sorptivity results at both 28 days and 120 days. The 28-day water sorptivity results are within the "Excellent" durability category for CEM I cements, and "Good" durability category for OPC cements. The water sorptivity results for this concrete exhibit the definite trend of reducing with time. Given the scatter of the results and the limited size of the data set it is not possible to comment strongly on the effect of the change in cement specification on this trend;
- The water sorptivity of GGBS concrete was marginally higher than that of FA concrete at 28 days, being within the "Good" durability category for both OPC and CEM I cements, with CEM I cement yielding lower water sorptivity results. At 120 days the water sorptivity results for GGBS concrete has reduced and is still marginally larger than the FA concrete results for both OPC and CEM I cements, with CEM I cement once again yielding marginally lower water sorptivity results. At 120 days the water sorptivity for GGBS concrete used with CEM I cement falls within the "Excellent" durability category, and OPC cement within the "Good" durability category. As for FA concrete GGBS concrete exhibits the trend of the water sorptivity reducing with time and the reduction is remarkably consistent with the FA concrete; and
- The CSF concrete produces water sorptivity results very similar to the GGBS concrete at both 28 days but higher at 120 days, within the "Good" durability category for both OPC and CEM I cements at 28 days, with CEM I cement marginally lower. At 120 days the water sorptivity is within the "Excellent" durability category for CEM I cement and in the "Good" durability category for OPC cement. CSF concrete exhibits very little change in water sorptivity with time.

6.4 INFLUENCE OF CURING METHOD

6.4.1 WALL SERIES

6.4.1.1 28-Day Results

Figure 46 shows the 28-day water sorptivity results for the OPC/GGBS, OPC/FA and OPC/CSF concretes (together with the environmental rating), with respect to the different curing methods.

From Figure 46, it is evident that as the environmental rating decreases the water sorptivity increases. This observation is consistent for all three concrete types and all the curing methods and indicates that the water sorptivity is affected by curing. The 28-day water sorptivity results for OPC/GGBS concrete is detailed in Table 50.

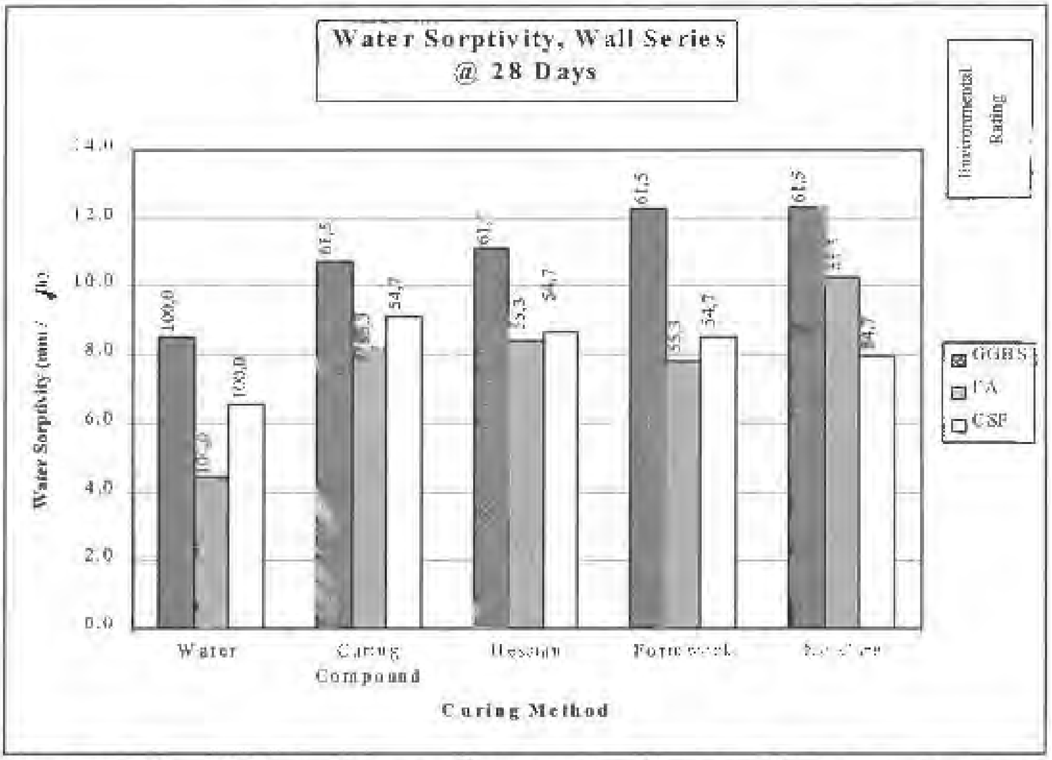


FIGURE 46: 28-DAY WATER SORPTIVITY RESULTS FOR THE VARIOUS CONCRETES (TOGETHER WITH THE ENVIRONMENTAL RATING), WITH RESPECT TO THE DIFFERENT CURING METHODS.

TABLE 50: 28-DAY WATER SORPTIVITY RESULTS FOR OPC/GGBS CONCRETE PER CURING METHOD.

CURING METHOD	WATER SORPTIVITY (mm/√h)	CURING REDUCTION RATIO
WATER	8,5	
COMPOUND	10,7	0,26
HESSIAN	11,1	0,31
FORMWORK	12,3	0,45
UNCURED	12,4	0,46

The results show that for the site-cured elements the water sorptivity results for the OPC/GGBS concrete fall within the "Poor" durability category. For wet curing the water sorptivity results fall inside the "Good" durability category.

The 28-day water sorptivity data for OPC/FA concrete are detailed in Table 51.

TABLE 51: 28-DAY WATER SORPTIVITY RESULTS FOR OPC/FA CONCRETE PER CURING METHOD.

CURING METHOD	WATER SORPTIVITY (mm/√h)	CURING REDUCTION RATIO
WATER	4,4	
COMPOUND	8,2	0,86
HESSIAN	8,4	0,91
FORMWORK	7,8	0,77
UNCURED	10,3	1,34

For wet curing the water sorptivity for OPC/FA concrete fall within the "Excellent" durability category. For the formwork, hessian and curing compound curing methods the water sorptivity falls within the "Good" durability category. For the no active curing condition the water sorptivity falls within the "Poor" durability category.

The 28-day water sorptivity results for OPC/CSF concrete are detailed in Table 52.

TABLE 52: 28-DAY WATER SORPTIVITY RESULTS FOR OPC/CSF CONCRETE PER CURING METHOD.

CURING METHOD	WATER SORPTIVITY (mm/√h)	CURING REDUCTION RATIO
WATER	6,6	
COMPOUND	9,1	0,38
HESSIAN	8,6	0,30
FORMWORK	8,5	0,29
UNCURED	8,0	0,21

The water sorptivity for the OPC/CSF concrete falls within the "Good" durability category for all of the curing methods.

For wet curing OPC/FA concrete yielded the lowest water sorptivity (4,4 mm/√h), followed by OPC/CSF concrete (6,6 mm/√h) and OPC/GGBS concrete (8,5 mm/√h).

For OPC/FA concrete the curing compound, hessian and formwork site-curing yielded water sorptivity results within a small range (7,8 mm/√h to 8,4 mm/√h) in the "Good" durability category. For wet curing "Excellent" durability properties were realised while for no-curing "Poor" properties were realised. This is an indication of the sensitivity of FA concrete to curing.

For the OPC/GGBS concrete the site-curing methods yielded "Poor" durability properties with more scatter between the site-cured results (10,7 mm/√h to 12,4 mm/√h), while wet curing yielded "Good" durability properties.

For the OPC/CSF concrete the site-curing methods yielded "Good" durability properties with very little scatter between the site-cured results (8,0 mm/√h to 9,1 mm/√h), while wet curing yielded a substantial reduction in durability properties (6,6 mm/√h).

Figure 47 shows the change (i.e. increase) in 28-day water sorptivity results for the various curing methods, and different concretes. The figure uses a "curing reduction ratio" which is the difference between the water sorptivity under consideration (site-curing methods) and the fully water-cured condition divided by the value for the fully water-cured condition. It is in effect a indicator of the reduction in curing effectiveness of a given curing method, in relation to the fully water-cured condition. Thus the larger a particular "curing reduction ratio", the larger the shift between the fully cured water sorptivity value and the water sorptivity value for the site-curing method under consideration.

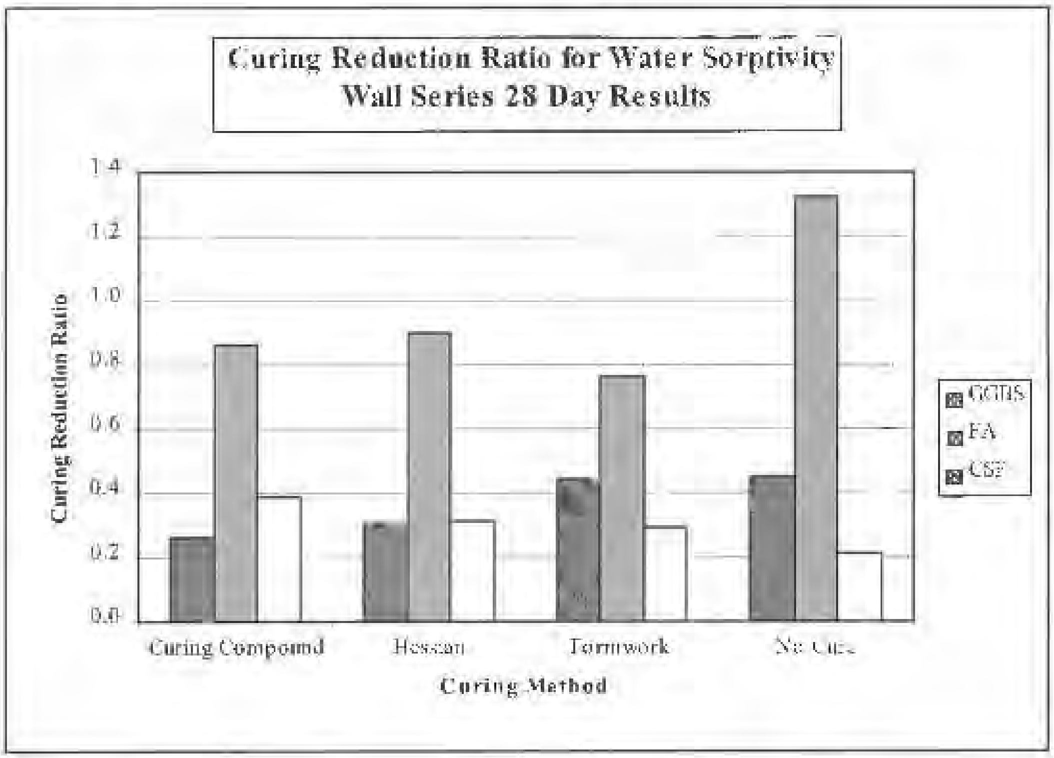


FIGURE 47: CHANGE IN 28-DAY WATER SORPTIVITY RESULTS FOR WALL SERIES PLOTTED AGAINST RESPECTIVE CURING METHOD.

The OPC/FA concrete exhibited the highest "curing reduction ratio" in water sorptivity per curing method. This is an indication of the sensitivity of the OPC/FA concrete to curing. The OPC/GGBS and OPC/CSF concretes yielded substantially lower "curing reduction ratio" results for the different curing methods, in comparison with the OPC/FA concrete. This once again points to the sensitivity of OPC/FA concrete to curing.

For the OPC/FA concrete the ratios can be broadly grouped. The no-cure condition yields the highest ratio while the formwork, hessian and curing compound curing methods yield smaller, roughly equal ratios. The common factor between formwork, hessian and curing compound curing is the possible masking effect of the curing method. In other words the curing method is able to reduce the influence of the external environmental condition by a barrier effect. It is plausible that the formwork and hessian curing methods would limit temperature and humidity variation during the period of curing, while the curing compound reduces the loss of moisture. On the other hand no-curing would offer no barrier.

For the OPC/CSF and OPC/GGBS concretes the ratio is remarkably consistent, possibly indicating that these two concretes exhibit little sensitivity to the site-curing methods utilised. Note that this observation is made within the context of the limited data presented here and for the particular environmental rating. Obviously fully curing the element in water results in a benefit to the water sorptivity.

Alexander et al[34] indicated that for uncured Western Cape concretes consisting of a blend of OPC/GGBS and OPC/FA of the same concrete grade, in the same proportions as used in this project, water sorptivity results in the region of 13,0 mm/√h were realised. Interestingly the water sorptivity results achieved in this study are markedly similar. In this project, OPC/FA concretes exhibited a marginal improvement but essentially yield similar durability properties. This confirms the sensitivity of the water sorptivity index to curing practices rather than material selection.

6.4.1.2 Conclusions Relating to 28-Day Results

Based on the observations and discussion and subject to the environmental conditions experienced by the elements, the following can be concluded:

- At 28 days the water sorptivity is affected by the curing method utilised;
- For the OPC/GGBS concrete the water sorptivity results at 28 days for the site-curing methods falls within the "Poor" durability category, while wet curing yields "Good" durability properties;
- For OPC/FA concrete the no-cure curing method yielded water sorptivity results at 28 days in the "Poor" durability category, while wet curing yield "Excellent" durability properties. The remainder of the site-curing methods yield "Good" durability properties;
- For OPC/CSF concrete the water sorptivity results at 28 days fall within the "Good" durability category;
- OPC/FA concretes exhibited the largest "curing reduction ratio" for each curing method. OPC/CSF and OPC/GGBS concretes exhibited a lower ratio for each curing method. Notwithstanding the variation in environmental rating for OPC/FA, OPC/CSF and OPC/GGBS concretes (55,3%, 61,5% and 54,7% respectively), OPC/FA concretes clearly exhibited the most sensitivity to curing (or rather lack of curing);
- Considering the "curing reduction ratio" for OPC/GGBS and OPC/CSF concretes, it appears that they exhibit similar, lower sensitivity to curing methods. This is with particular reference to the environmental exposure conditions experienced; and
- The use of hessian, formwork retention and application of a curing compound, as curing methods are more beneficial than no-curing for OPC/FA concretes. For OPC/CSF and OPC/GGBS concretes there appeared to be no clear benefit afforded by any one of the site-curing

methods used. However the use of full wet-curing afforded clear benefits for these two concretes.

6.4.1.3 120-Day Results

Figure 48 shows the 120-day water sorptivity results for the OPC/GGBS, OPC/FA and OPC/CSF concretes (together with the environmental rating), plotted against curing method.

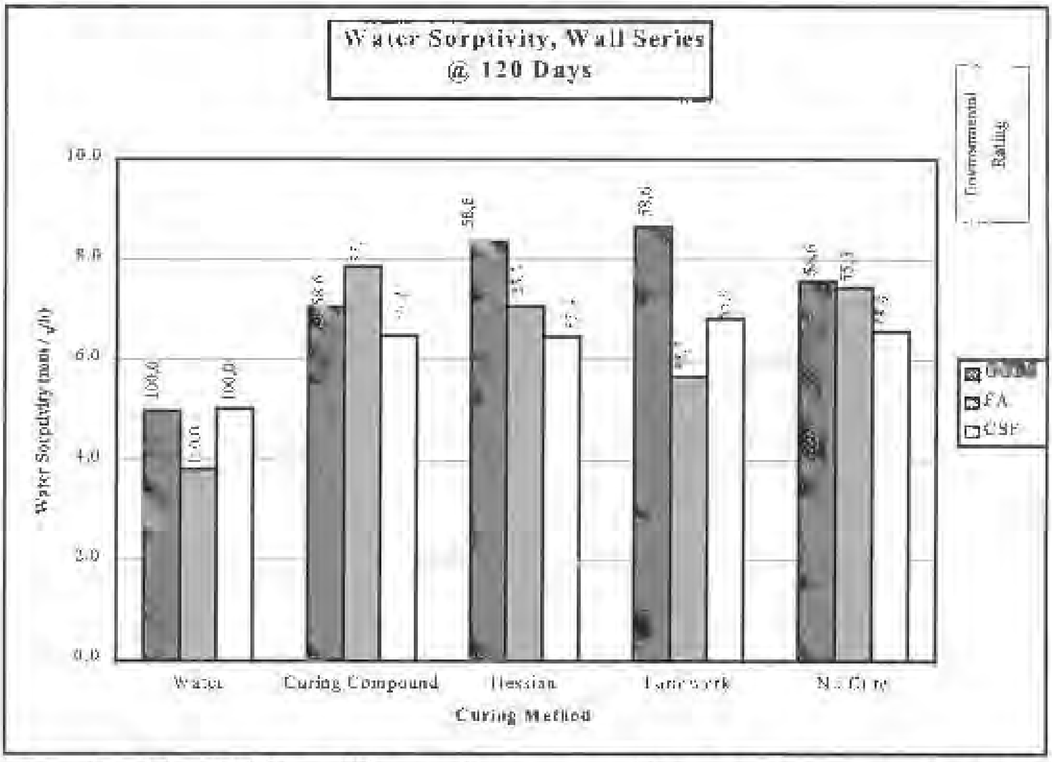


FIGURE 48: 120-DAY WATER SORPTIVITY RESULTS FOR THE VARIOUS CONCRETES (TOGETHER WITH THE ENVIRONMENTAL RATING), WITH REFERENCE TO THE DIFFERENT CURING METHODS.

The 120-day water sorptivity results for OPC/GGBS concrete are detailed in Table 53.

TABLE 53: 120-DAY WATER SORPTIVITY RESULTS FOR OPC/GGBS CONCRETE PER CURING METHOD.

CURING METHOD	WATER SORPTIVITY (mm/√h)	CURING REDUCTION RATIO
WATER	5,0	
COMPOUND	7,0	0,40
HESSIAN	8,4	0,68
FORMWORK	8,7	0,74
UNCURED	7,6	0,52

With the exception of wet curing, the water sorptivity for the OPC/GGBS concretes falls within the "Good" durability category. For wet curing the water sorptivity falls within the "Excellent" durability category. Considering the change in water sorptivity with time (using the 120-day data as a base) decreases of the order of 40% to 60% have occurred for the site elements, while for the wet-cured cubes the decrease is about 70%. The various curing methods exhibit different decreases in water sorptivity with time, but these improvements do not match the substantial improvements, under wet-cured conditions.

The 120-day water sorptivity results for OPC/FA concrete are detailed in Table 54.

TABLE 54: 120-DAY WATER SORPTIVITY RESULTS FOR OPC/FA CONCRETE PER CURING METHOD.

CURING METHOD	WATER SORPTIVITY (mm/√h)	CURING REDUCTION RATIO
WATER	3,8	
COMPOUND	7,9	1,08
HESSIAN	7,1	0,87
FORMWORK	5,7	0,50
UNCURED	7,4	0,95

For the wet and formwork curing the water sorptivity falls within the "Excellent" durability category. The water sorptivity result for formwork curing, within the "Excellent" durability category, is not consistent with the remainder of the data set. For the hessian, curing compound and no-curing method the water sorptivity falls in the "Good" durability category. Considering the change in water sorptivity (using the 120-day data as a base) decreases of the order of 10% to 50% occur. While it has been shown that the OPC/FA concrete are sensitive to curing method, it is interesting to note that these mixes show less percentage change from 28 days to 120 days than the OPC/GGBS concrete.

The 120-day water sorptivity results for OPC/CSF concrete are detailed in Table 55.

TABLE 55: 120-DAY WATER SORPTIVITY RESULTS FOR OPC/CSF CONCRETE PER CURING METHOD.

CURING METHOD	WATER SORPTIVITY (mm/√h)	CURING REDUCTION RATIO
WATER	5,0	
COMPOUND	6,5	0,30
HESSIAN	6,5	0,30
FORMWORK	6,8	0,36
UNCURED	6,6	0,32

The water sorptivity for the OPC/CSF concrete falls within the "Good" durability category, for all of the curing methods, while for wet-cured cubes the water sorptivity is within the "Excellent" durability category. Considering the change in water sorptivity (using the 120-day data as a base) decreases of the order of 20% to 40% occur. However the 120-day water sorptivity results are low, so that the change in absolute terms from 28 days to 120 days are small.

For the wet-cured condition OPC/FA concrete yielded the lowest water sorptivity (3,8 mm/√h), followed by OPC/GGBS concrete (5,0 mm/√h) and OPC/CSF (5,0 mm/√h). As discussed previously all the concretes fall well within the "Excellent" durability category.

For the site-curing methods the water sorptivity results for OPC/CSF concrete exhibit a small range (6,5 mm/√h to 6,8 mm/√h), and fall into the "Good" durability category. These are the lowest water sorptivity results for the wall series data. This is followed by OPC/FA concrete, which also exhibits a reasonably small range (5,7 mm/√h to 7,9 mm/√h), and falls into the "Good" durability category. For the OPC/GGBS concrete the water sorptivity results are marginally higher and exhibit a larger spread than those of the OPC/CSF and OPC/FA concrete (7,0 mm/√h to 8,7 mm/√h), and fall into the "Good" durability category.

Figure 49 shows the change in 120-day water sorptivity results for the various curing methods, for the OPC/GGBS, OPC/FA and OPC/CSF concretes.

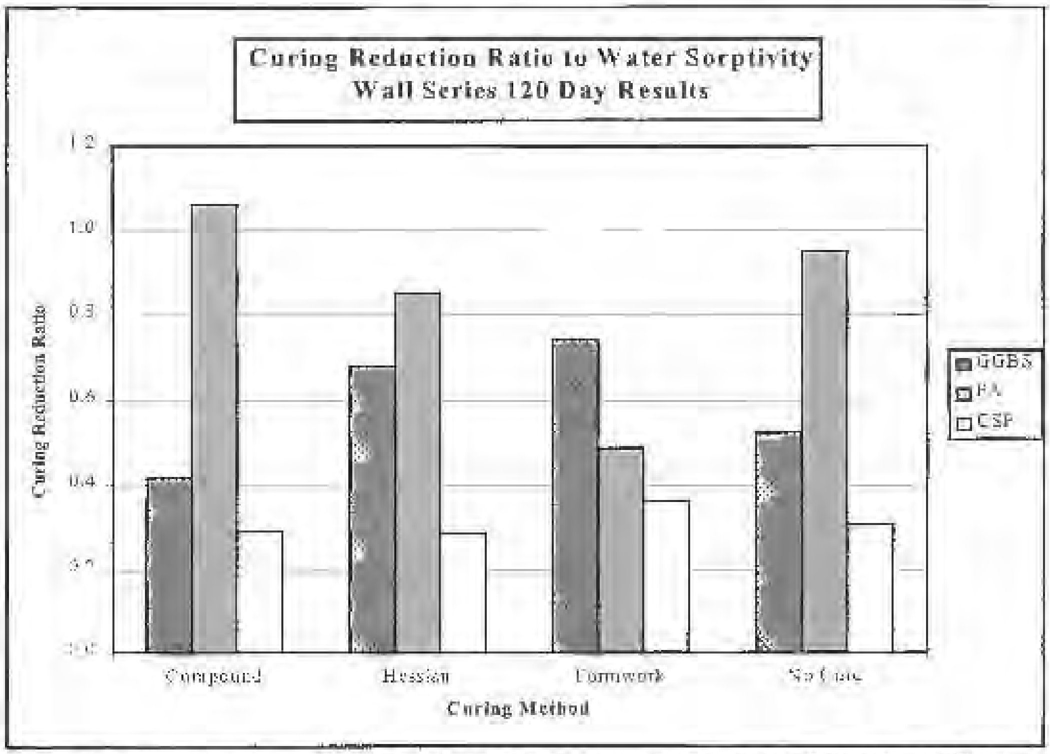


FIGURE 49: CHANGE 120-DAY WATER SORPTIVITY RESULTS FOR WALL SERIES PLOTTED AGAINST RESPECTIVE CURING METHOD.

Considering the data presented in Figure 42, OPC/FA concretes exhibited the highest "curing reduction ratio" in water sorptivity per curing method. As mentioned previously in this section, this is an indication of the sensitivity of the OPC/FA concrete to curing. The OPC/GGBS concretes yielded a smaller "curing reduction ratio" for water sorptivity per curing method, in comparison with the OPC/FA concrete. This is an indication of the lower sensitivity of the OPC/GGBS concrete to curing. For the OPC/CSF concrete the "curing reduction ratio" for water sorptivity for each curing method is remarkably consistent, indicating that the concretes exhibit very little sensitivity to the curing method utilised.

For the OPC/FA concrete the ratios can be broadly grouped. The no-cure, hessian and curing compound curing condition yields the highest ratio roughly equal while the formwork curing methods yields a smaller ratio.

For the OPC/GGBS concrete the ratios can be broadly grouped. The hessian and formwork curing condition yields the highest ratio equal, while the curing compound and no active curing methods yields a smaller roughly equal ratio.

For the OPC/CSF concrete the ratios are remarkably consistent, possibly indicating that this concrete exhibit little sensitivity to the site-curing method utilised. Note that this observation is made within the context of the limited data presented here and for the particular environmental rating. Obviously fully curing the element in water results in a benefit to the water sorptivity.

6.4.1.4 Conclusions Relating to 120-Day Results

Based on the observations and discussion the following can be concluded:

- At 120 days the water sorptivity is not affected, in practical terms, by the site-curing method utilised. The wet curing however has a noticeable influence on the results;
- For the OPC/GGBS, OPC/FA and OPC/CSF concretes the water sorptivity results at 120 days for the site-curing methods falls within the "Good" durability category, while wet curing yields "Excellent" durability properties;
- OPC/FA concretes exhibited the largest "curing reduction ratio" for water sorptivity per curing method. OPC/GGBS concretes exhibited a smaller "curing reduction ratio" for water sorptivity per curing method with OPC/CSF concrete exhibiting the lowest ratio. Unfortunately given that the environmental rating for OPC/FA, OPC/CSF and OPC/GGBS concretes vary (55,3%, 55,9% and 58,6% respectively) it is not possible to be conclusive in this regard. However it would appear that OPC/FA concrete exhibited the most sensitivity to curing; and
- For all of the concrete types (GGBS, FA and CSF) no clear pattern is evident relating to the extent of benefit afforded by the various site-curing methods. It must be noted however that the results represent "Good" durability properties even for no active curing.

6.4.1.5 General Conclusions Relating to Site Cured Wall Samples

Based on the observations and discussion in the preceding section of this chapter the following can be concluded, relative to site cured wall samples. These are considered as the key findings for the first part of the second section of this chapter:

- OPC/GGBS concrete in walls exhibited definite sensitivity to curing at both 28 and 120 days. At 28 days the water sorptivity for various site-cured samples are within the "Poor" durability category, while at 120 days all the results are within the "Good" durability category. No site-curing method emerges as being more beneficial than another at both 28 days and 120 days;

- OPC/FA concrete exhibited a substantial sensitivity to curing at 28 and 120 days, and was the most sensitive of the three concretes used. At 28 and 120 days the water sorptivity for various site-cured samples are within the "Good" durability category. The uses of hessian, formwork retention and the application of curing compound are more beneficial than no active curing at 28 days. At 120 days however no clear trend emerges with respect to the most efficient site-curing method; and
- OPC/CSF concrete exhibited the least sensitivity to curing at 28 and 120 days, of the three concretes used. At 28 and 120 days the water sorptivity for various site-cured samples are within the "Good" durability category. At 28 and 120 days however no clear trend emerges with respect to the most efficient site-curing method.

6.4.2 SLAB SERIES

6.4.2.1 28-Day Results

The data is discussed for the elements cast using OPC and CEM I separately. The slab series 1&2 were cast using OPC while series 3&4 were cast using CEM I.

6.4.2.2 Observations and Discussion: Series Cast Using OPC Concretes

Figure 50 shows the 28-day water sorptivity results for the OPC/GGBS (Slabs A1 and A2), OPC/FA (Slabs B1 and B2) and OPC/CSF (Slabs C1 and C2) concretes (together with environmental rating), with reference to the curing methods.

The 28-day water sorptivity results for the OPC/BBBS concrete are given in Table 56.

TABLE 56: 28-DAY WATER SORPTIVITY RESULTS FOR OPC/GGBS CONCRETE PER CURING METHOD.

CURING METHOD	WATER SORPTIVITY (SLAB A1 SERIES) mm/√h	WATER SORPTIVITY (SLAB A2 SERIES) mm/√h	MEAN WATER SORPTIVITY mm/√h	MEAN CURING REDUCTION RATIO
WATER	7,2	5,7	6,5	
COMPOUND	7,8	7,2	7,5	0,16
HESSIAN	8,5	8,2	8,4	0,30
SAND	8,3	6,7	7,5	0,16
UNCURED	7,1	7,6	7,4	0,15

All the results are similar and fall in a narrow band, inside the "Good" durability category. No site-curing method appears to offer advantages in practical terms. The variation between the results for the site curing methods are small in real terms and the marginal variation between the lowest and highest water sorptivity indicates a reduced sensitivity to curing.

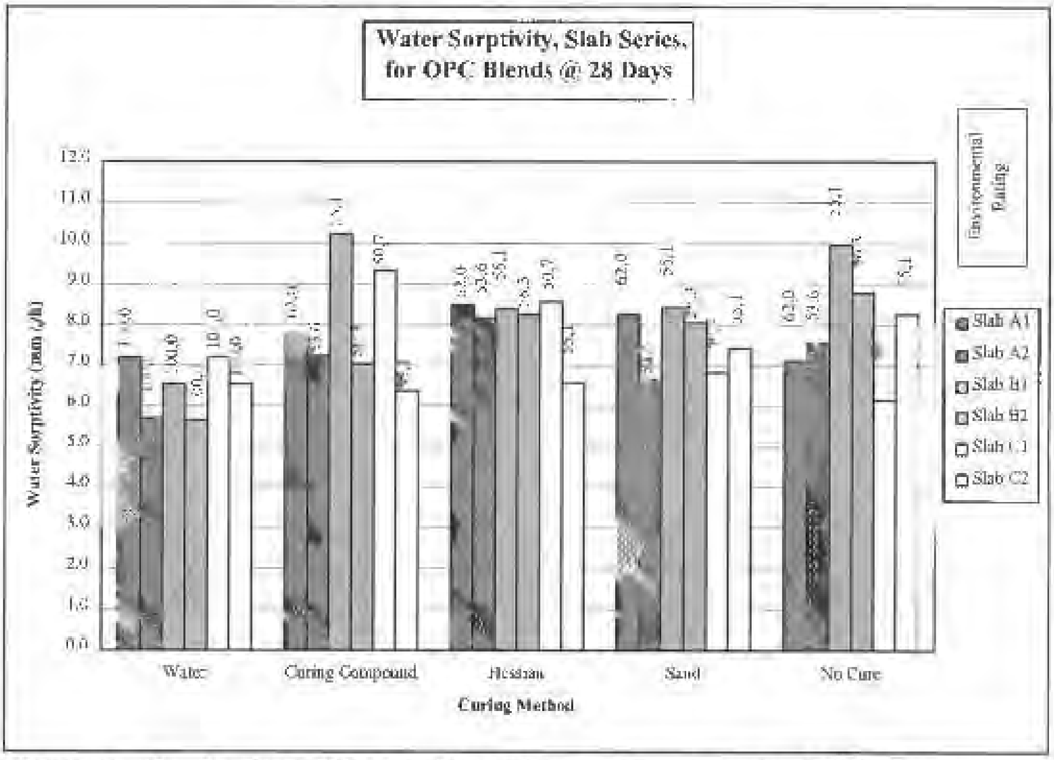


FIGURE 50: 28-DAY WATER SORPTIVITY RESULTS FOR OPC CONCRETES (TOGETHER WITH THE ENVIRONMENTAL RATING), PLOTTED AGAINST VARIOUS CURING METHODS.

The 28-day water sorptivity results for the OPC/FA concrete are given in Table 57.

TABLE 57: 28-DAY WATER SORPTIVITY RESULTS FOR OPC/FA CONCRETE PER CURING METHOD.

CURING METHOD	WATER SORPTIVITY (SLAB B1 SERIES) mm/√h	WATER SORPTIVITY (SLAB B2 SERIES) mm/√h	MEAN WATER SORPTIVITY mm/√h	MEAN CURING REDUCTION RATIO
WATER	6,5	5,6	6,1	
COMPOUND	10,2	7,0	8,6	0,42
HESSIAN	8,4	8,3	8,4	0,39
SAND	8,4	8,1	8,3	0,36
UNCURED	10,0	8,8	9,4	0,55

The results for wet curing are closer to the "Excellent" durability category, while the remainder of the site cured results are within the "Good" durability category, with no-curing yielding the highest result (poorest properties). There is a noticeable variation between the lowest and highest water sorptivity result, indicating the sensitivity of OPC/FA concrete to curing. Sand curing is the most effective site-curing method followed by hessian, the application of curing compound and no active curing (in order of effectiveness).

The 28-day water sorptivity results for the OPC/CSF concrete are given in Table 58.

TABLE 58: 28-DAY WATER SORPTIVITY RESULTS FOR OPC/CSF CONCRETE PER CURING METHOD.

CURING METHOD	WATER SORPTIVITY (SLAB C1 SERIES) mm/√h	WATER SORPTIVITY (SLAB C2 SERIES) mm/√h	MEAN WATER SORPTIVITY mm/√h	MEAN CURING REDUCTION RATIO
WATER	7,2	6,5	6,9	
COMPOUND	9,3	6,4	7,9	0,15
HESSIAN	8,6	6,6	7,6	0,11
SAND	6,8	7,4	7,1	0,04
UNCURED	6,1	8,3	7,2	0,05

The results for wet curing are closer to the "Excellent" durability category, while the remainder of the site cured results are within the "Good" durability category. Sand curing is the most effective site-curing method followed by no active curing, hessian curing and the application of curing compound (in order of effectiveness), although in practical terms there is no real difference. There is a marginal variation between the lowest and highest water sorptivity result, indicating the reduced sensitivity of this concrete to curing.

Figure 51 shows the mean change in 28-day water sorptivity results for the various curing methods, for the different concretes and is based on the mean curing reduction ratios presented in Tables 51 through 53.

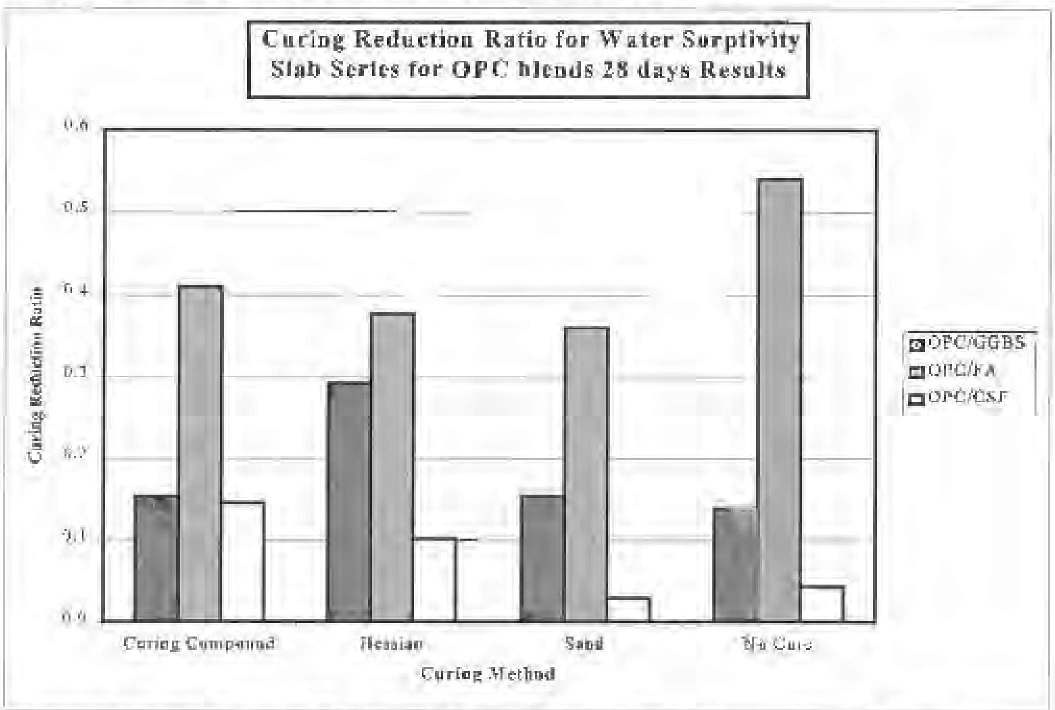


FIGURE 51: CHANGE IN 28-DAY WATER SORPTIVITY RESULTS FOR SLAB SERIES CAST USING OPC, PLOTTED AGAINST RESPECTIVE CURING METHOD.

The OPC/FA concrete exhibited the highest "curing reduction ratio" in comparison to OPC/GGBS and OPC/CSF concrete, indicating the sensitivity of OPC/FA concrete to curing. The OPC/FA concrete indicates that sand, hessian and the application of curing compound are all more effective than no active curing. OPC/GGBS concrete does not mirror this trend but rather indicates that the application of curing compound, sand curing and no active curing is more effective than hessian curing. The OPC/CSF concrete indicates that sand and no active curing is more beneficial than hessian and the application of curing compound.

While some variation in results is evident, generally the water sorptivity falls into a relatively narrow band within the "Good" and "Excellent" durability categories. The values for OPC/FA concrete, although more sensitivity to curing, also fall within the "Good" durability category.

Mackechnie[18] indicated that for uncured Western Cape concretes consisting of a blend of OPC/GGBS and OPC/FA of the same concrete grade, in the same proportions as used in this project, water sorptivity results in the region of 12,0 mm/√h were realised. Interestingly the water sorptivity results achieved for the slab series, for GGBS and FA concretes, are lower than this value.

6.4.2.3 Observations and Discussion: Series Cast Using CEM I Concretes

Figure 52 shows the 28-day water sorptivity results for the CEMI/GGBS (slab A3 and A4), CEMI/FA (slab B3 and B4) and CEMI/CSF (slab C3 and C4) concretes (together with environmental rating), with reference to the curing methods.

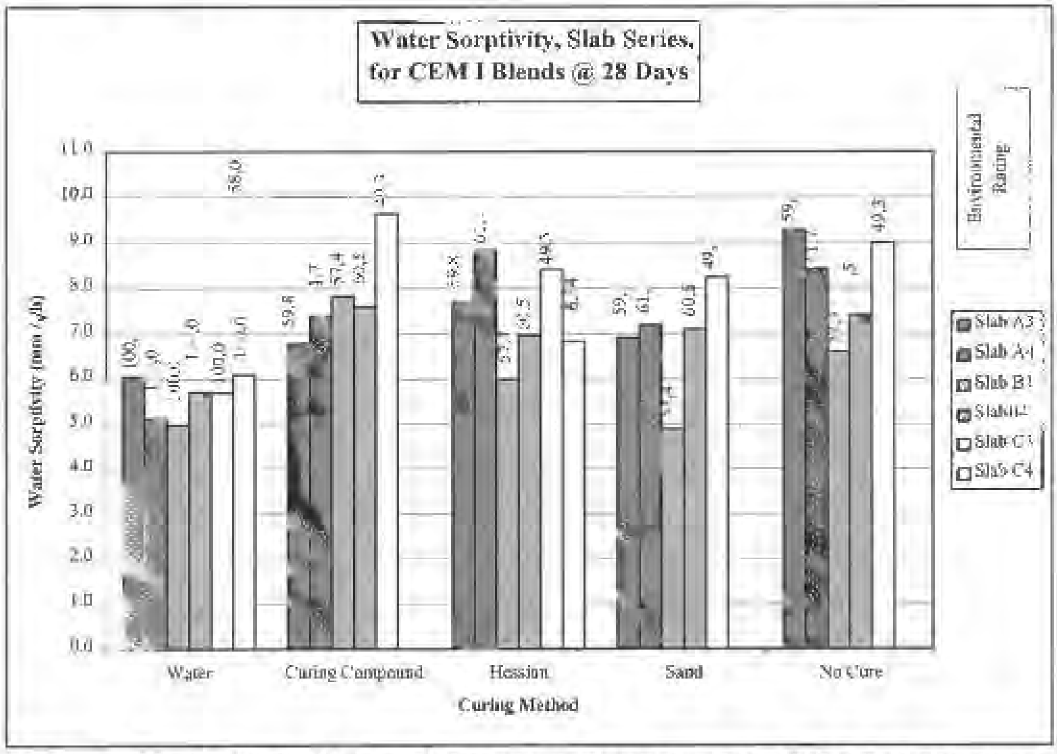


FIGURE 52: 28-DAY WATER SORPTIVITY RESULTS FOR CEM I CONCRETES (TOGETHER WITH THE ENVIRONMENTAL RATING), PLOTTED AGAINST VARIOUS CURING METHODS.

The 28-day water sorptivity results for the CEM I/GGBS concrete are given in Table 59.

TABLE 59: 28-DAY WATER SORPTIVITY RESULTS FOR CEM I/GGBS CONCRETE PER CURING METHOD.

CURING METHOD	WATER SORPTIVITY (SLAB A3 SERIES) mm/√h	WATER SORPTIVITY (SLAB A4 SERIES) mm/√h	MEAN WATER SORPTIVITY mm/√h	MEAN CURING REDUCTION RATIO
WATER	6,1	5,1	5,6	
COMPOUND	6,8	7,4	7,1	0,27
HESSIAN	7,7	8,8	8,3	0,47
SAND	6,9	7,2	7,1	0,27
UNCURED	9,3	8,4	8,9	0,59

The results for wet curing are within the "Excellent" durability category, while the remainder of the results are within the "Good" durability category, with no active curing yielding the highest (poorest properties) result. Sand curing is the most effective site-curing method followed by the application of curing compound, hessian and no active curing (in order of effectiveness). There is a noticeable variation between the lowest and highest water sorptivity result indicating the increased sensitivity of GGBS to curing, when used with CEM I cement. When these results are compared to the OPC results, at the same element age, it is noted that marginally better results were achieved for wet curing, while noticeably poorer results were achieved for no active curing. Thus the use of CEM I cement has increased the sensitivity of GGBS concrete to curing.

The 28-day water sorptivity results for the CEM I/FA concrete are given in Table 60.

TABLE 60: 28-DAY WATER SORPTIVITY RESULTS FOR CEM I/FA CONCRETE PER CURING METHOD.

CURING METHOD	WATER SORPTIVITY (SLAB B3 SERIES) mm/√h	WATER SORPTIVITY (SLAB B4 SERIES) mm/√h	MEAN WATER SORPTIVITY mm/√h	MEAN CURING REDUCTION RATIO
WATER	5,0	5,7	5,4	
COMPOUND	7,8	7,6	7,7	0,43
HESSIAN	6,0	7,0	6,5	0,20
SAND	4,9	7,1	6,0	0,12
UNCURED	6,6	7,4	7,0	0,30

The results for wet curing are within the "Excellent" durability category, while the remainder of the results are within the "Good" durability category, with curing compound curing yielding the highest result (poorest properties). Sand curing is the most effective site-curing method followed by hessian curing, no active curing and the application of curing compound (in order of effectiveness). There is a noticeable variation between the lowest and highest water sorptivity result. When these results are compared to the OPC results, at the same element age, it is noted that generally the use of CEM I cement results in marginally lower i.e. more favourable water sorptivity results.

The 28-day water sorptivity results for the CEM I/CSF concrete are given in Table 61.

TABLE 61: 28-DAY WATER SORPTIVITY RESULTS FOR CEM I/CSF CONCRETE PER CURING METHOD.

CURING METHOD	WATER SORPTIVITY (SLAB C3 SERIES) mm/√h	WATER SORPTIVITY (SLAB C4 SERIES) mm/√h	MEAN WATER SORPTIVITY mm/√h	MEAN CURING REDUCTION RATIO
WATER	5,7	6,1	5,9	
COMPOUND	9,6	No data	9,6	0,63
HESSIAN	8,4	6,8	7,6	0,29
SAND	8,2	No data	8,2	0,39
UNCURED	9,0	No data	9,0	0,53

The results for wet curing are within the "Excellent" durability category, while the remainder of the results are within the "Good" durability category, with curing compound curing yielding the highest (poorest properties) result. Hessian curing is the most effective site-curing method followed by sand curing, no active curing and the application of curing compound (in order of effectiveness). There is a noticeable variation between the lowest and highest water sorptivity result, indicating the sensitivity to curing. When these results are compared to the OPC results, at the same element age, it is noted that the use of CEM I cement results in marginally higher i.e. less favourable results for no active curing but similar results for wet curing.

Figure 53 shows the mean change in 28-day water sorptivity results for the various curing methods, for the different concretes and is based on the mean curing reduction ratios presented in Tables 54 through 56.

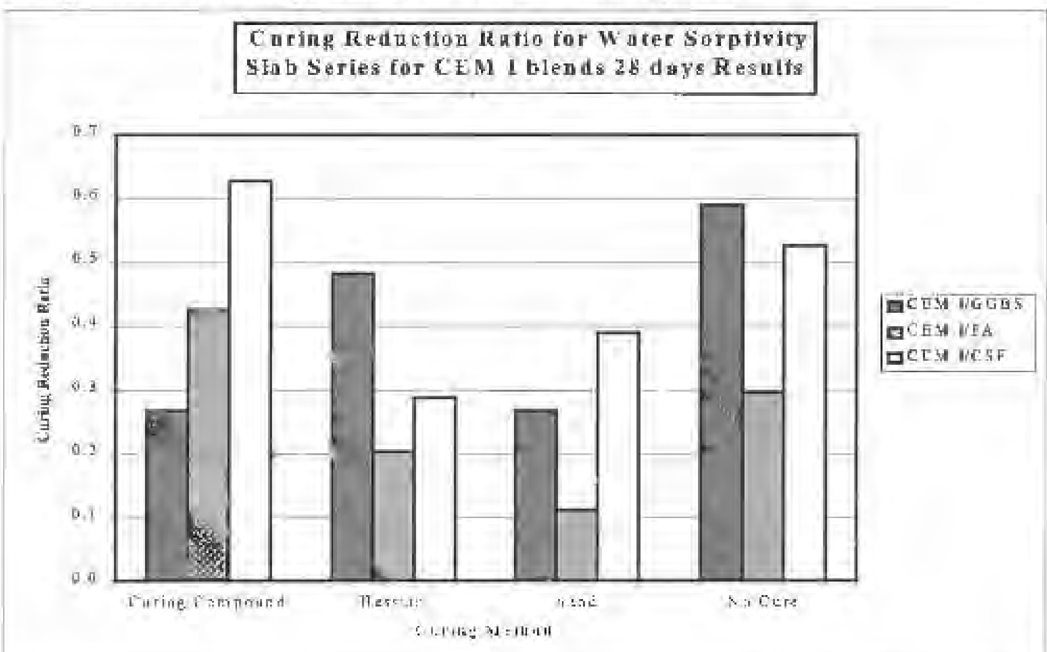


FIGURE 53: CHANGE IN 28-DAY WATER SORPTIVITY RESULTS FOR SLAB SERIES CAST USING CEM I, PLOTTED AGAINST RESPECTIVE CURING METHOD.

Given the scatter of results it is not possible to indicate which concrete type is more or less sensitive to curing in relation to another. The OPC/FA concrete indicates that sand and hessian curing is more effective than no active curing or the application of curing compound. OPC/GGBS concrete indicates that sand curing and the application of curing compound is more effective than hessian curing or no active curing. The OPC/CSF concrete indicates that sand and hessian curing is more beneficial than no active curing or the application of curing compound. Thus, taken on balance, sand and hessian curing appear to be more effective than the application of curing compound and no active curing.

While some variation in results is evident the water sorptivity falls generally into a narrow band within the "Good" and "Excellent" durability categories. This is possibly one of the drawbacks of the results in that they are "Too Good" and thus do not indicate the beneficial effect of the curing methods utilised. It must be stressed however, as established in Chapter 4, that in a national context, the environment in East London is more favourable to developing good durability properties than in Johannesburg by comparison. It is thus crucial to view the beneficial effect of curing, in relation to the environmental conditions pertaining to the curing period.

The use of CEM I cement has resulted in an increase in sensitivity of the GGBS and CSF concretes to curing, while the FA concrete exhibits a similar sensitivity to curing as noted for the OPC cement.

6.4.2.4 Conclusions Relating to 28-Day Results

Based on the foregoing observations and discussion, and subject to the environmental conditions experienced, the following can be concluded:

- GGBS concrete in slabs exhibited definite sensitivity to curing at 28 days for OPC and CEM I cements. The water sorptivity for the various site-cured samples are within the "Good" durability category for both OPC and CEM I cement. For wet curing the OPC cements produce "Good" durability properties while the CEM I cements produce "Excellent" properties. The use of CEM I cement with GGBS results in a noticeable reduction in water sorptivity for wet curing but an increase in water sorptivity for no active curing, when compared to OPC cement. No active curing is more beneficial than sand curing, the application of curing compound or hessian curing (in order of effectiveness) for OPC/GGBS concretes at 28 days. For the CEM I/GGBS concrete at 28 days this trend is not repeated in that the application of curing compound and sand curing is more beneficial than hessian curing or no active curing (in order of effectiveness);
- FA concrete in slabs exhibited definite sensitivity to curing at 28 days for OPC and CEM I cements. The water sorptivity for the various site-cured samples are within the "Good" durability category for both OPC and CEM I cement. For wet curing the OPC cements produce "Good" durability properties while the CEM I cements produce "Excellent" properties. The use of CEM I cement with FA results in a noticeable reduction in water sorptivity when compared to OPC cement. The sand curing is more beneficial than hessian curing, the application of curing compound or no active curing (in order of effectiveness) for OPC/FA concretes at 28 days. For the CEM I concrete at 28 days this trend is repeated in that sand curing

is more beneficial than hessian curing, no active curing and the application of curing compound (in order of effectiveness);

- CSF concrete in slabs exhibited definite sensitivity to curing at 28 days for OPC and CEM I cements. The water sorptivity for the various site-cured samples are within the "Good" durability category for both OPC and CEM I cement. For wet curing the OPC cements produce "Good" durability properties while the CEM I cements produce "Excellent" properties. Sand curing is more beneficial than no active curing, hessian curing or the application of curing compound (in order of effectiveness) for OPC/CSF concretes at 28 days. For the CEM I/CSF concrete at 28 days this trend is not repeated in that hessian curing is more beneficial than sand curing, no active curing or the application of curing compound; and
- FA concrete when used with OPC cement exhibited a marked sensitivity to curing when compared to the GGBS and CSF concrete used with OPC cement. For CEM I cement however FA concrete did not exhibit this trend and showed similar sensitivity to curing as for CSF concretes when used with CEM I cement. However GGBS concrete when used with CEM I cement, exhibited marked sensitivity to curing, relative to OPC cement.

6.4.3 SLAB SERIES

6.4.3.1 120-Day Results

The data are discussed for the elements cast using OPC and CEM I separately. The slab series 1&2 were cast using OPC while series 3&4 were cast using CEM I.

6.4.3.2 Observations and Discussion: Series Cast Using OPC Concrete

Figure 54 shows the 120-day water sorptivity results for the three concretes (together with environmental rating), with reference to the curing methods.

The 120-day water sorptivity results for the OPC/GGBS concrete are given in Table 62.

TABLE 62: 120-DAY WATER SORPTIVITY RESULTS FOR OPC/GGBS CONCRETE PER CURING METHOD.

CURING METHOD	WATER SORPTIVITY (SLAB A1 SERIES) mm/√h	WATER SORPTIVITY (SLAB A2 SERIES) mm/√h	MEAN WATER SORPTIVITY mm/√h	MEAN CURING REDUCTION RATIO
WATER	4,0	6,3	5,2	
COMPOUND	5,2	6,9	6,1	0,17
HESSIAN	6,2	(Outlier)	6,2	0,20
SAND	6,5	5,5	6,0	0,17
UNCURED	4,2	6,5	5,4	0,04

All the results are similar and fall into a narrow band, within the "Good" and "Excellent" durability categories. Wet, sand and no active curing are in the "Excellent" durability category, while hessian and curing compound curing are within the

"Good" durability category. No active curing is the most effective site-curing method followed by sand curing, the application of curing compound and hessian curing (in order of effectiveness). However, little variation is evident between the various site-cured results and they effectively yield the same durability properties. Similarities exist when the effectiveness of the various site-curing methods are compared with the 28-day results in that the ranking or order of curing effectiveness is unchanged with time. The change in water sorptivity results relative to the 28-day results, using the 120-day results as a base, indicates that no active curing shows the largest change while the application of curing compound the least.

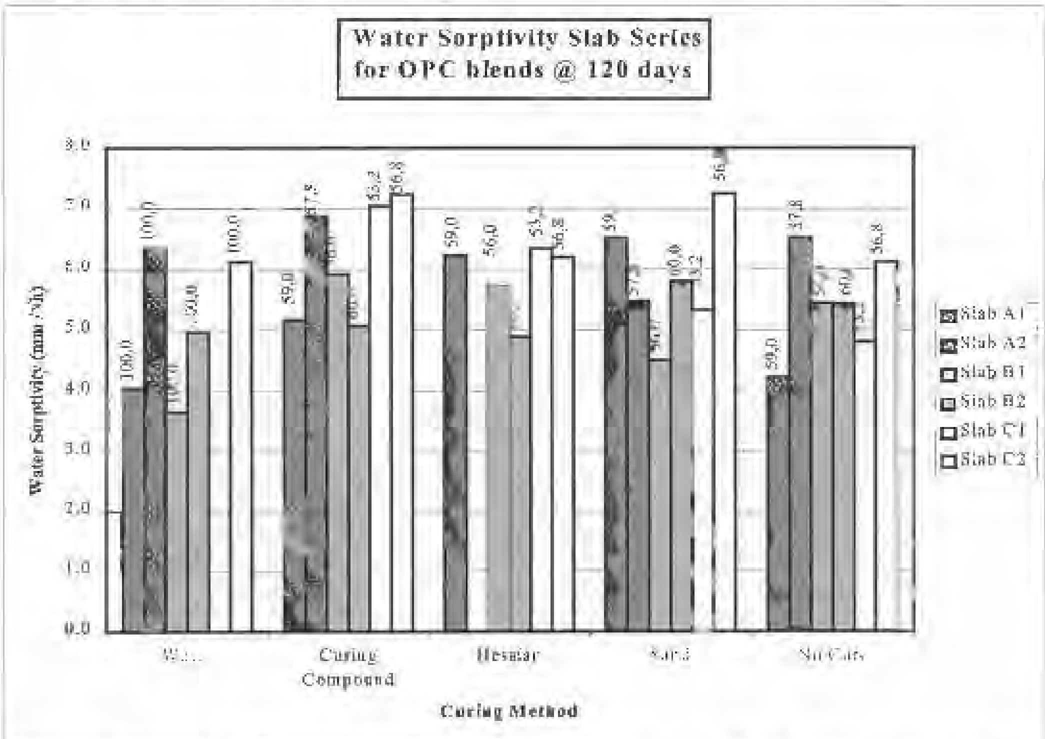


FIGURE 54: 120-DAY WATER SORPTIVITY RESULTS FOR OPC CONCRETES (TOGETHER WITH THE ENVIRONMENTAL RATING), PLOTTED AGAINST VARIOUS CURING METHODS.

The 120-day water sorptivity results for the OPC/ FA concrete are given in Table 63.

TABLE 63: 120-DAY WATER SORPTIVITY RESULTS FOR OPC/FA CONCRETE PER CURING METHOD.

CURING METHOD	WATER SORPTIVITY (SLAB B1 SERIES) mm/√h	WATER SORPTIVITY (SLAB B2 SERIES) mm/√h	MEAN WATER SORPTIVITY mm/√h	MEAN CURING REDUCTION RATIO
WATER	3,7	5,0	4,4	
COMPOUND	5,9	5,1	5,5	0,25
HESSIAN	5,8	4,9	5,4	0,23
SAND	4,5	5,8	5,2	0,18
UNCURED	5,4	5,4	5,4	0,23

All the site-cured results are similar and fall into a fairly narrow band, within the "Excellent" durability category, while wet curing is in the "Excellent" durability category and is somewhat better than the site cured results. Sand curing is the most effective site-curing method followed by hessian curing, no active curing and the application of curing compound (in order of effectiveness). However, little variation is evident between the various site-cured results and they effectively yield the same durability properties. When comparing the effectiveness of the various site-curing methods with the 28-day results, similarities exist in that relative ranking of sand and hessian curing is unchanged with time. For the application of curing compound and no active curing however, the ranking or order of curing effectiveness has altered with time. The change in water sorptivity results relative to the 28-day results, using the 120-day results as a base, indicate that no active curing shows the largest change while wet curing the least.

The 120-day water sorptivity results for the OPC/CSF concrete are given in Table 64.

TABLE 64: 120-DAY WATER SORPTIVITY RESULTS FOR CSF CONCRETE PER CURING METHOD.

CURING METHOD	WATER SORPTIVITY (SLAB C1 SERIES) mm/√h	WATER SORPTIVITY (SLAB C2 SERIES) mm/√h	MEAN WATER SORPTIVITY mm/√h	MEAN CURING REDUCTION RATIO
WATER	No data	6,1	6,1	
COMPOUND	7,0	7,2	7,1	0,16
HESSIAN	6,3	6,2	6,3	0,03
SAND	5,3	7,2	6,3	0,03
UNCURED	4,8	6,1	5,5	

All the results are similar and fall into a narrow band, within the "Good" and "Excellent" durability categories. No active curing produces "Excellent" properties, while the remainder of the curing methods produce "Good" properties. No active curing is the most effective site-curing method followed by hessian, sand curing and the application of curing compound (in order of effectiveness). While variation is evident between the various site-cured results, with the exception of no active curing they effectively yield the same durability properties. This is an indication that the absence of active curing has not unduly penalised the site concrete at 120 days, and this is true for GGBS and FA concretes also.

Similarities exist when the effectiveness of the various site-curing methods are compared with the 28-day results in that the ranking or order of curing effectiveness is similar with time. Both sand and no active curing are shown to be more effective than hessian or the application of curing compound and this remains constant with time. The change in water sorptivity results, relative to the 28-day results using the 120-day results as a base, indicate that hessian curing shows the largest change while sand curing the least.

Figure 55 shows the mean change in 120-day water sorptivity results for the various curing methods, and different binders and is based on mean curing reduction ratio as presented in Tables 57 through 59.

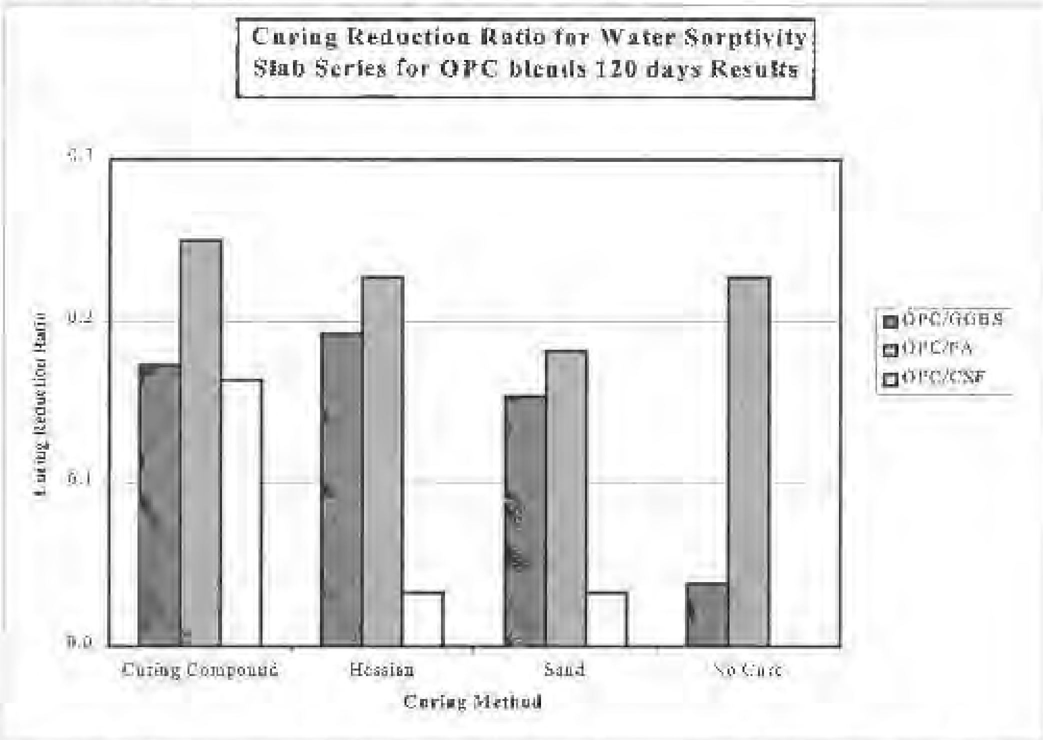


FIGURE 55: CHANGE IN 120-DAY WATER SORPTIVITY RESULTS FOR SLAB SERIES CAST USING OPC, PLOTTED AGAINST RESPECTIVE CURING METHOD.

OPC/GGBS and OPC/FA concretes generally exhibited a higher "curing reduction ratio" relative to OPC/CSF concrete. This is an indication of the sensitivity of these concretes to wet curing. The OPC/GGBS concrete indicates that no active curing is the most effective site-curing method, followed by sand curing, the application of curing compound and hessian curing, all indicating very similar ratios. OPC/FA concrete indicates that sand curing is the most effective, followed by hessian curing, no active curing and the application of curing compound, also indicating a similar ratio. For OPC/CSF concrete no "curing reduction ratio" is indicated for no active curing since it is negative. A negative curing reduction ratio indicates that the site-curing method results in a more favourable durability property than wet curing. Considering the data this has been shown to be unlikely, hence negative ratios are considered anomalous. The sand and hessian curing for OPC/CSF concrete is shown to be the most effective site-curing methods with similar ratios, followed by the application of curing compound, with a noticeable increase in ratio.

The "curing reduction ratio" for OPC/FA concrete has reduced from 0,36 to 0,55 at 28 days to 0,18 to 0,25 at 120 days. For OPC/GGBS concrete the ratio has reduced with time from 0,04 to 0,20 at 28 days to 0,18 to 0,25 at 120 days. For OPC/CSF concrete the curing reduction ratio has remained constant with time from 0,04 to 0,15 at 28 days to 0,03 to 0,16 at 120 days.

6.4.3.3 Observations and Discussion: Series Cast Using CEM I Concrete

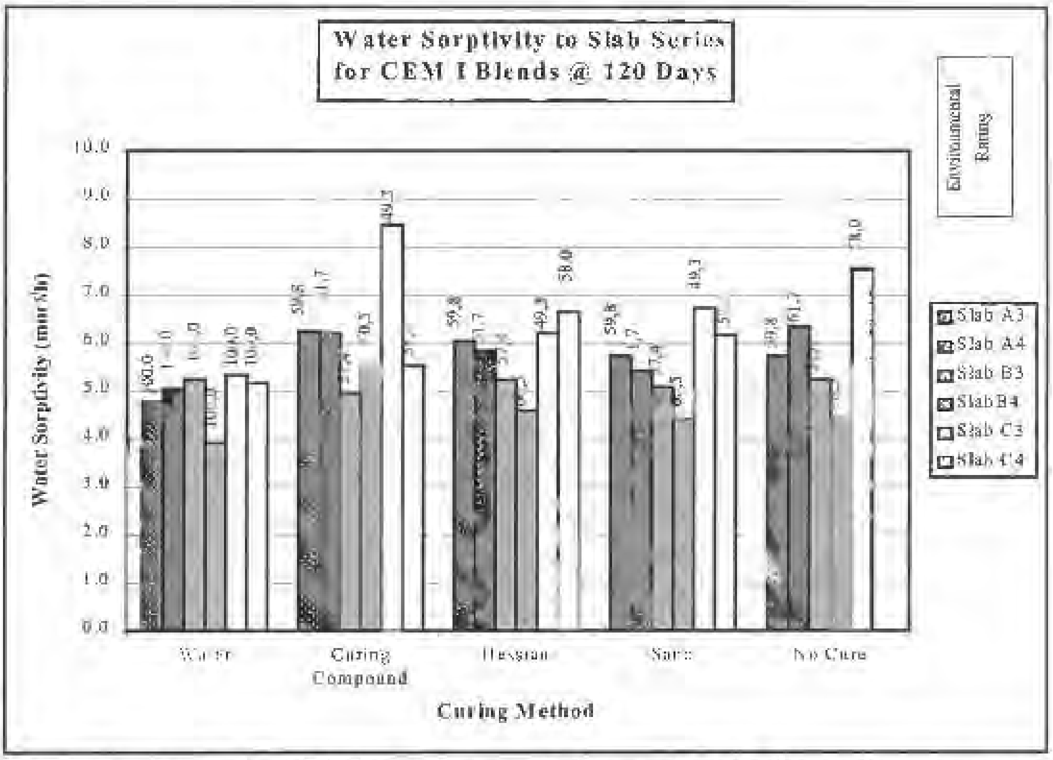


Figure 56 shows the 120-day water sorptivity results for the various concrete (together with environmental rating), with reference to the curing methods.

FIGURE 56: 120-DAY WATER SORPTIVITY RESULTS FOR CEM I CONCRETE (TOGETHER WITH THE ENVIRONMENTAL RATING), PLOTTED AGAINST VARIOUS CURING METHODS.

The 120-day water sorptivity results for the GGBS/CEM I concrete are given in Table 65.

TABLE 65: 120-DAY WATER SORPTIVITY RESULTS FOR CEM I/GGBS CONCRETE PER CURING METHOD.

CURING METHOD	WATER SORPTIVITY (SLAB A3 SERIES) mm/√h	WATER SORPTIVITY (SLAB A4 SERIES) mm/√h	MEAN WATER SORPTIVITY mm/√h	MEAN CURING REDUCTION RATIO
WATER	4,8	5,0	4,9	
COMPOUND	6,2	6,2	6,2	0,27
HESSIAN	6,0	5,8	5,9	0,20
SAND	5,7	5,4	5,6	0,14
UNCURED	5,7	6,3	6,0	0,22

Wet curing develops the most favourable result, within the "Excellent" durability category, improved in relation to the site cured concretes. All the site-cured results are similar and fall into a narrow band in the "Excellent" and "Good" durability categories. Sand curing, hessian curing and no active curing (in order of effectiveness) are marginally more effective than the application of curing compound and are within the "Excellent" category. The application of curing compound curing result is within the "Good" durability category.

When compared with the 28-day results for CEM I/GGBS concrete it is noted that sand curing is the only curing method that has not altered in relative ranking. When these results are compared to the OPC cement results at the same element age, no visible effect is evident and the results are practically "indistinguishable".

The 120-day water sorptivity results for the CEM I/FA concrete are given in Table 66.

TABLE 66: 120-DAY WATER SORPTIVITY RESULTS FOR CEM I/FA CONCRETE PER CURING METHOD.

CURING METHOD	WATER SORPTIVITY (SLAB B3 SERIES) mm/√h	WATER SORPTIVITY (SLAB B4 SERIES) mm/√h	MEAN WATER SORPTIVITY mm/√h	MEAN CURING REDUCTION RATIO
WATER	5,2	3,9	4,6	
COMPOUND	4,9	5,5	5,2	0,13
HESSIAN	5,2	4,6	4,9	0,07
SAND	5,1	4,4	4,8	0,04
UNCURED	5,2	4,4	4,8	0,04

Wet curing develops the most favourable result, within the "Excellent" durability category, marginally improved in relation to the site cured concretes. All the site-cured results are similar and fall into a narrow band inside the "Excellent" durability categories. Sand curing is shown to be the most effective site-curing method, marginally more effective than no active curing, hessian curing and the application of curing compound. Notwithstanding the above, little variation is evident between the various site-cured results and they effectively yield the same durability properties.

When compared with the 28-day results for CEM I/FA concrete it is noted that sand curing and curing compound curing are the only curing methods that have not altered in relative ranking. When these results are compared to the OPC cement results at the same element age, no visible effect is evident and the results are practically "indistinguishable".

The 120-day water sorptivity results for the CEM I/CSF concrete are given in Table 67.

TABLE 67: 120-DAY WATER SORPTIVITY RESULTS FOR CEM I/CSF CONCRETE PER CURING METHOD.

CURING METHOD	WATER SORPTIVITY (SLAB C3 SERIES) mm/√h	WATER SORPTIVITY (SLAB C4 SERIES) mm/√h	MEAN WATER SORPTIVITY mm/√h	MEAN CURING REDUCTION RATIO
WATER	5,3	5,2	5,3	
COMPOUND	8,5	5,5	7,0	0,33
HESSIAN	6,2	6,7	6,5	0,23
SAND	6,7	6,2	6,5	0,23
UNCURED	7,6	No data	7,6	0,43

Wet curing develops the most favourable result, within the "Excellent" durability category, noticeably improved in relation to the site cured concretes. All the site-cured results are similar and fall into a narrow band inside the "Good" durability categories. Sand and hessian curing are shown to be the most effective site-curing methods, marginally more effective than the application of curing compound and the no active curing. Notwithstanding the above, little variation is evident between the sand, hessian and curing compound curing, while the no active curing exhibits a noticeable shift. However the results are practically similar and they effectively yield the same durability properties.

When compared with the 28-day results for CEM I/CSF concrete it is noted no site-curing methods have not retained their relative ranking. When these results are compared to the OPC cement results at the same element age, no visible effect is evident and the results are practically "indistinguishable".

Figure 57 shows the change in 120-day water sorptivity results for the various curing methods, for the various concretes and is based on the mean curing reduction ratio reflected in Tables 60 through 62.

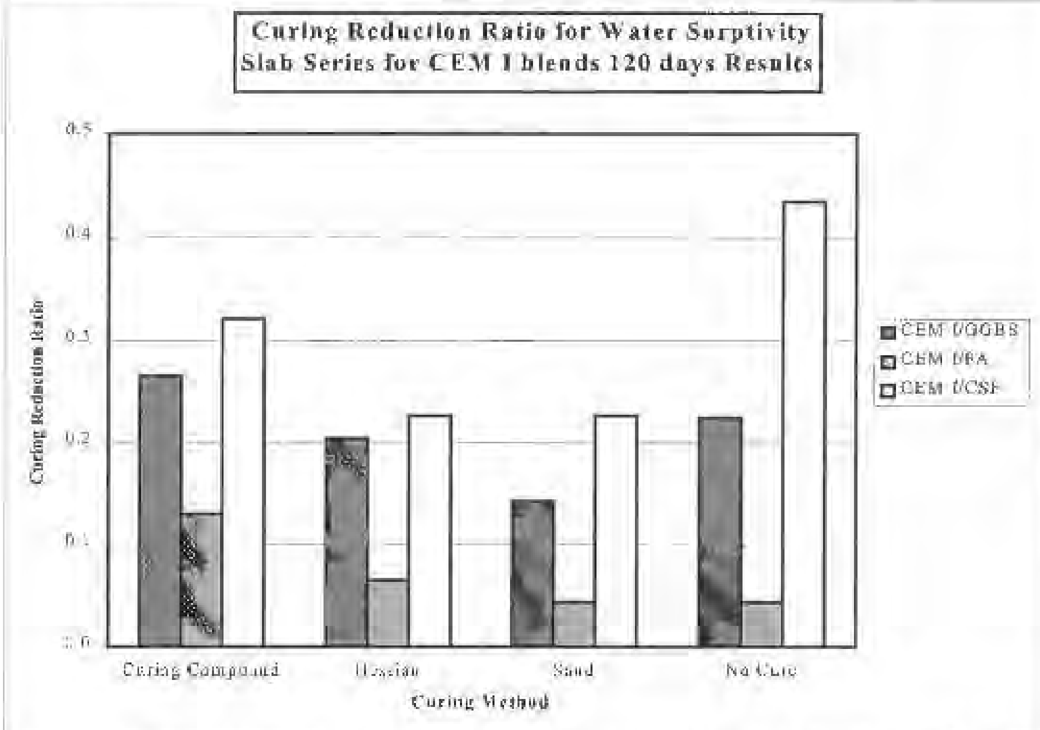


FIGURE 57: CHANGE 120-DAY WATER SORPTIVITY RESULTS FOR SLAB SERIES CAST USING CEM I, PLOTTED AGAINST RESPECTIVE CURING METHOD.

CEM I/GGBS and CEM I/CSF concretes generally exhibited a higher "curing reduction ratio" in comparison with OPC/FA concretes, indicating the sensitivity of these concretes to curing. Since the various site cured results are very similar this is in effect an indication of the sensitivity of the concrete to wet curing.

The CEM I/GGBS concrete indicates that sand curing is the most effective site-curing method, followed by hessian curing, no active curing and the application of curing compound, all indicating very similar ratios. CEM I/FA concrete indicates that sand curing and no active curing are equally and marginally more effective than hessian curing and the application of curing compound, also indicating a similar ratio. The CEM I/CSF concrete indicates that sand and hessian curing are more effective than the application of curing compound and no active curing. In this case a substantial variation exists in "curing reduction ratio" between no active curing and the other site-curing methods.

The curing reduction ratio for CEM I/GGBS concrete has reduced from 0,27 to 0,59 at 28 days to 0,14 to 0,27 at 120 days. CEM I/FA concrete has indicated a reduction with time from 0,12 to 0,43 at 28 days to 0,04 to 0,13 at 120 days. For CEM I/CSF concrete the "curing reduction ratio" has reduced marginally with time from 0,29 to 0,63 at 28 days to 0,23 to 0,43 at 120 days.

The use of CEM I cement has had no change in the sensitivity of the GGBS concrete while it has reduced the sensitivity of the FA concrete to curing and increased the sensitivity of the CSF concrete to curing, at 120 days.

6.4.3.4 Conclusions Relating to 120-Day Results

Based on the observation and discussion and subject to the environmental conditions experienced by the elements, the following can be concluded:

- GGBS concrete in slabs exhibited definite sensitivity to curing at 120 days when used with OPC and CEM I cements. The water sorptivity for the various site-cured samples are within the "Excellent" and "Good" durability category for both OPC and CEM I cement. The change in cement type has had no influence on the GGBS concrete water sorptivity results. No active curing is more beneficial than sand curing, the application of curing compound curing or hessian curing (in order of effectiveness) for OPC/GGBS concretes at 120 days. For the CEM I concrete at 120 days sand curing is more beneficial than hessian curing, no active curing or the application of curing compound (in order of effectiveness). While marginal variations in durability quality are evident for site cured concrete, practically no site-curing method is more effective than another and the results are generally "indistinguishable". In terms of change in water sorptivity with time, the OPC and CEM I cements exhibit a similar reduction in water sorptivity with element age and does not follow any set trend;
- FA concrete in slabs exhibited definite sensitivity to curing at 120 days for OPC and CEM I cements. The water sorptivity for the various site-cured samples are within the "Excellent" durability category for both OPC and CEM I cement. The change in cement type has had no influence on the FA concrete water sorptivity results. Sand curing is more beneficial than hessian curing, no active curing and the application of curing compound (in order of effectiveness) for OPC/FA concretes at 120 days. For the CEM I concrete at 120 days sand curing is more beneficial than no active curing, hessian curing and the application of curing compound (in order of effectiveness). As noted for GGBS concretes, the durability properties of the various site cured concretes are generally "indistinguishable". In terms of change in water sorptivity with time, the OPC and CEM I cements exhibit a similar reduction in water sorptivity with element age and does not follow any set trend; and
- CSF concrete in slabs exhibited definite sensitivity to curing at 120 days for OPC and CEM I cements. The water sorptivity for the various site-

cured samples are within the "Good" durability category for OPC and CEM I cements. Once again the influence of cement type has resulted in no variation in durability properties. No active curing is more beneficial than sand curing, the application of curing compound or hessian curing (in order of effectiveness), for OPC/CSF concretes at 120 days. For the CEM I concrete at 120 days sand and hessian curing are more beneficial than the application of curing compound and no active curing (in order of effectiveness). As noted for the GGBS and FA concretes little variability exists between the results for the site cured concretes and they are practically the same. In terms of change in water sorptivity with time, the OPC and CEM I cements exhibit a similar reduction in water sorptivity with element age and does not follow any set trend.

6.4.3.5 General Conclusions Relating to Site Cured Slab Samples

Based on the observations and discussion in the proceeding section of this chapter the following can be concluded, relative to site cured slab samples, and are considered as the key findings for this chapter:

- GGBS concrete in slabs exhibited definite sensitivity to curing at both 28 days, exhibited by the variation between wet and site cured results, and 120 days, when used with both OPC and CEM I cements. This was more evident for CEM I cement at 28 days but at 120 days this trend was not repeated and the results were practically similar for both cement types. At 28 days the water sorptivity for the various site-cured results is within the "Good" durability category for both OPC and CEM I cements. The water sorptivity results reduce with time and at 120 days they are within the "Good" and "Excellent" durability category for both OPC and CEM I cements. At 28 days no site-curing method is discernibly more effective than another. At 120 days the use of sand curing is consistently more beneficial than the application of curing compound or hessian curing (in order of effectiveness) for both the OPC and CEM I cements. The change in cement type appears to have little or no influence on the reduction of the water sorptivity with time;
- FA concrete in slabs exhibited definite sensitivity to curing at both 28 days, exhibited by the variation between wet and site cured results, and 120 days, when used with both OPC and CEM I cements. This was more evident for OPC cement at 28 days but at 120 days this trend was not repeated and the results were practically similar for both cement types. At 28 days the water sorptivity for the various site-cured results is within the "Good" durability category for OPC cement and within the "Good" and "Excellent" durability category for CEM I cements. The water sorptivity results reduce with time and at 120 days they are within the "Excellent" durability category for both OPC and CEM I cements. At 28 days sand curing is consistently more beneficial than hessian curing, the application of curing compound or no active curing for both OPC and CEM I cements. At 120 days sand curing is consistently more beneficial than the application of curing compound or hessian curing for both the OPC and CEM I cements. The change in cement type appears to have little or no influence on the reduction of the water sorptivity with time;
- CSF concrete in slabs exhibited definite sensitivity to curing at both 28 days, exhibited by the variation between wet and site cured results, and

120 days, when used with both OPC and CEM I cements. This was more evident for CEM I cement at 28 days but at 120-day this trend was not repeated and the results were practically similar for both cement types. At 28 days the water sorptivity for the various site-cured results is within the "Good" durability category for OPC and CEM I cements. The water sorptivity results reduce with time and at 120 days they are within the "Good" durability category for both OPC and CEM I cements. At 28 days sand curing is consistently more beneficial than hessian curing, the application of curing compound or no active curing for both OPC and CEM I cements. At 120 days sand curing is consistently more beneficial than the application of curing compound or hessian curing for both the OPC and CEM I cements. The change in cement type appears to have little or no influence on the reduction of the water sorptivity with time;

- It should be noted that the relatively good results that quite frequently occurred with no active curing can be attributed to some degree to the favourable environmental conditions at East London at the time, and poorer uncured results are likely, in hotter, drier and less humid environments. Likewise, instances of poor performance of curing compound curing, compared to no cure, can possibly be attributed to the barrier effect at the curing compound precluding the access of favourable, moist, environmental conditions to the element, particularly during the early ages of curing.

6.4.3.6 General Summary Relating to Site Cured Samples (Walls and Slabs)

Table 68 represents a summary of all the data used in the this chapter and can be considered to be a summary of findings

TABLE 68: GENERAL SUMMARY OF WATER SORPTIVITY RESULTS FOR ALL CONCRETE TYPES AND VARIOUS CURING REGIMES.

		OPC CEMENT				CEM I CEMENT	
		WALL SERIES		SLAB SERIES		SLAB SERIES	
		28 DAYS	120 DAYS	28 DAYS	120 DAYS	28 DAYS	120 DAYS
GGBS BINDER	CURING * SENSITIVITY	0,3 to 0,5	0,4 to 0,8	0,2 to 0,3	0,1 to 0,2	0,3 to 0,6	0,2 to 0,3
GGBS BINDER	WATER SORPTIVITY VALUES (mm/√ h)	8,5 to 12,4 Water (8,5) Hessian (11,1) C. Comp. (10,7) Formwork (12,3) Uncured (12,4)	5,0 to 8,7 Water (5,0) C. Comp. (7,0) Uncured (7,6) Hessian (8,4) Formwork (8,7)	6,5 to 8,4 Uncured (7,4) Water (6,5) C. Comp. (7,5) Sand (7,5) Hessian (8,4)	5,2 to 6,2 Water (5,2) Uncured (5,4) Sand (6,0) C. Comp. (6,1) Hessian (6,2)	5,6 to 8,9 Water (5,6) Sand (7,1) C. Comp. (7,1) Hessian (8,3) Uncured (8,9)	4,9 to 6,2 Water (4,9) Sand (5,6) Hessian (5,9) Uncured (6,0) C. Comp. (6,2)
GGBS BINDER	CHANGE IN RESULTS WITH TIME		32% to 70% reduction		23% to 39% reduction		14% to 48% reduction
FA BINDER	CURING * SENSITIVITY	0,8 to 1,3	0,5 to 1,1	0,4 to 0,6	0,2 to 0,3	0,2 to 0,4	0,1 to 0,2
FA BINDER	WATER SORPTIVITY VALUES (mm/√ h)	4,4 to 10,3 Water (4,4) Formwork (7,8) C. Comp. (8,2) Hessian (8,4) Uncured (10,3)	3,8 to 7,9 Water (3,8) Formwork (5,7) Hessian (7,1) Uncured (7,4) C. Comp. (7,9)	6,1 to 9,4 Water (6,1) Sand (8,3) Hessian (8,4) C. Comp. (8,6) Uncured (9,4)	4,4 to 5,4 Water (4,4) Sand (5,2) Hessian (5,4) Uncured (5,4) C. Comp. (5,5)	5,4 to 7,7 Water (5,4) Sand (6,0) Hessian (6,5) Uncured (7,0) C. Comp. (7,7)	4,6 to 5,2 Water (4,6) Sand (4,8) Uncured (4,8) Hessian (4,9) C. Comp. (5,2)
FA BINDER	CHANGE IN VALUES WITH TIME		4% to 40% reduction		39% to 74% reduction		17% to 48% reduction

Table 68: General Summary of Water Sorptivity Results for All Concrete Types and Various Curing Regimes. (Cont.)

		OPC Cement				CEM I Cement	
		Wall Series		Slab Series		Slab Series	
		28 Days	120 Days	28 Days	120 Days	28 Days	120 Days
CSF Binder	Curing * Sensitivity	0,2 to 0,4	0,3 to 0,4	0,1 to 0,2	0,1 to 0,2	0,4 to 0,6	0,2 to 0,5
	Water Sorptivity Values (mm/√h)	6,6 to 9,1 Water (6,6) Uncured (8,0) Formwork (8,5) Hessian (8,6) C. Comp. (9,1)	5,0 to 6,8 Water (5,0) C. Comp. (6,5) Hessian (6,5) Uncured (6,6) Formwork (6,8)	6,9 to 7,9 Water (6,9) Sand (7,1) Uncured (7,2) Hessian (7,6) C. Comp. (7,9)	5,5 to 7,1 Uncured (5,5) Water (6,1) Sand (6,3) C. Comp. (7,1) Hessian (6,3)	5,9 to 9,6 Water (5,9) Sand (8,2) Hessian (8,4) Uncured (9,0) C. Comp. (9,6)	5,3 to 7,6 Water (5,3) Sand (6,5) Hessian (6,5) C. Comp. (7,0) Uncured (7,6)
	Change in Values with Time		21% to 40% reduction		11% to 31% reduction		11% to 27% reduction

* Note The curing sensitivity is indicated by the "curing reduction ratio".

CHAPTER 7

OXYGEN PERMEABILITY INDEX RESULTS

7.1 INFLUENCE OF WATER/BINDER RATIO

7.1.1 OXYGEN PERMEABILITY INDEX RESULTS AT 28 DAYS

Table 69 shows the water/binder ratios required to achieve a characteristic compressive strength of 30 MPa for the wall series and 35 MPa for the slab series, for the three concrete types.

TABLE 69: WATER/BINDER RATIOS FOR WALL AND SLAB ELEMENTS.

BINDER TYPE	WATER/BINDER RATIO	
	WALL SERIES	SLAB SERIES
OPC/GGBS	0,50	0,46
OPC/FA	0,50	0,47
OPC/CSF	0,57	0,54

Figure 58 shows the 28-day oxygen permeability index results for wet-cured cubes, plotted against the respective water/binder ratio, for the three binder types.

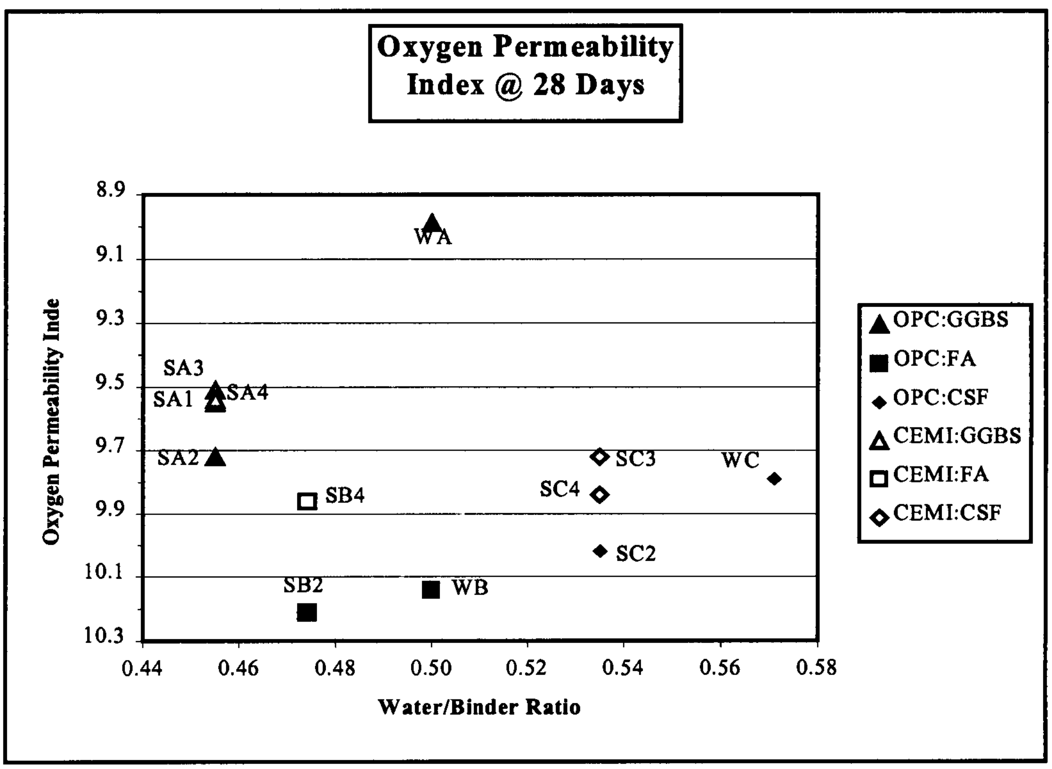


FIGURE 58: OXYGEN PERMEABILITY INDEX RESULTS AT 28 DAYS PLOTTED AGAINST WATER/BINDER RATIO FOR WET-CURED CUBES.

The result for wall A appears anomalous (8,99) when compared with the other results despite the statistical analysis indicating the data can be included. The discussion that follows, while addressing issues of water/binder ratio will also make reference to discernible trends in relation to binder type. This is further amplified in section 7.2.

The GGBS concretes exhibit a spread of results rather than a distinct grouping, related to the change in cement manufacture specification, while the FA concretes exhibit a distinct grouping. However the absence of a full set of results makes it difficult to comment decisively regarding the effect of the change in cement type. CSF concretes exhibit a definite grouping of results with a shift (from ~ 9,80 to ~ 10,00) between the two groups. In terms of the coefficient of permeability (k) this shift represents a change of ~ 60 %. It would thus appear that OPC cement has the effect of increasing (i.e. improving) the oxygen permeability index.

For the slab series the OPC/GGBS concrete yields oxygen permeability index results in the range of 9,55 to 9,72. The OPC/FA concrete yields a result of 10,21 and the OPC/CSF concrete a result of 10,02. The OPC/FA concrete yields the highest (most favourable) oxygen permeability index results followed by OPC/CSF concrete (a change of ~ 55 % in k relative to OPC/FA). OPC/GGBS concretes exhibit the lowest (poorest) results (a change of ~ 275 % in k relative to OPC/FA).

For the slab series the CEM I/GGBS concrete yields oxygen permeability index results in the range of 9,51 to 9,54. The CEM I/FA concrete yields a result of 9,86 and the CEM I/CSF concrete results in the range of 9,72 to 9,84. The CEM I/FA concrete yields the highest (most favourable) oxygen permeability index results followed by CEM I/CSF concrete (a change of ~ 20 % in k relative to CEM I/FA). CEM I/GGBS exhibit the lowest (poorest) results (a change of ~ 115 % in k relative to CEM I/FA).

For the wall series the OPC/FA concrete yields an oxygen permeability index of 10,14 and the OPC/CSF concrete an oxygen permeability index of 9,79. In terms of k the difference between these two results is ~ 125 %.

As a general characterisation[33], oxygen permeability index above 10,0 is considered to provide "Excellent" durability properties, above 9,5 and below 10,0 is considered "Good", below 9,5 is considered "Poor" and below 9,0 is considered "Very Poor". All the results for OPC/FA concrete fall inside the "Excellent" durability category, while the remainder of the results are inside the "Good" durability category.

Ignoring the results for elements cast using CEM I cement and comparing the results for slabs and walls cast using OPC cement, it is noted that as the water/binder ratio decreases (the quantity of binder increases) the oxygen permeability index increases (improves), for a given binder.

When comparing the above data with currently available oxygen permeability data, from the Western Cape[18], for 28-day wet-cured samples, it was noted that the GGBS concretes, for this project, exhibited noticeably poorer results (of the order of between two and five times, based on k). The FA concrete results, for this project, were also lower (of the order of two times, based on k) and the CSF concrete results, for this project, were also poorer (of the order of three to four times, based on k).

7.1.2 OXYGEN PERMEABILITY INDEX RESULTS AT 120 DAYS

Figure 59 shows the 120-day oxygen permeability index results for wet-cured cubes plotted against the respective water/binder ratio, for the three binder types.

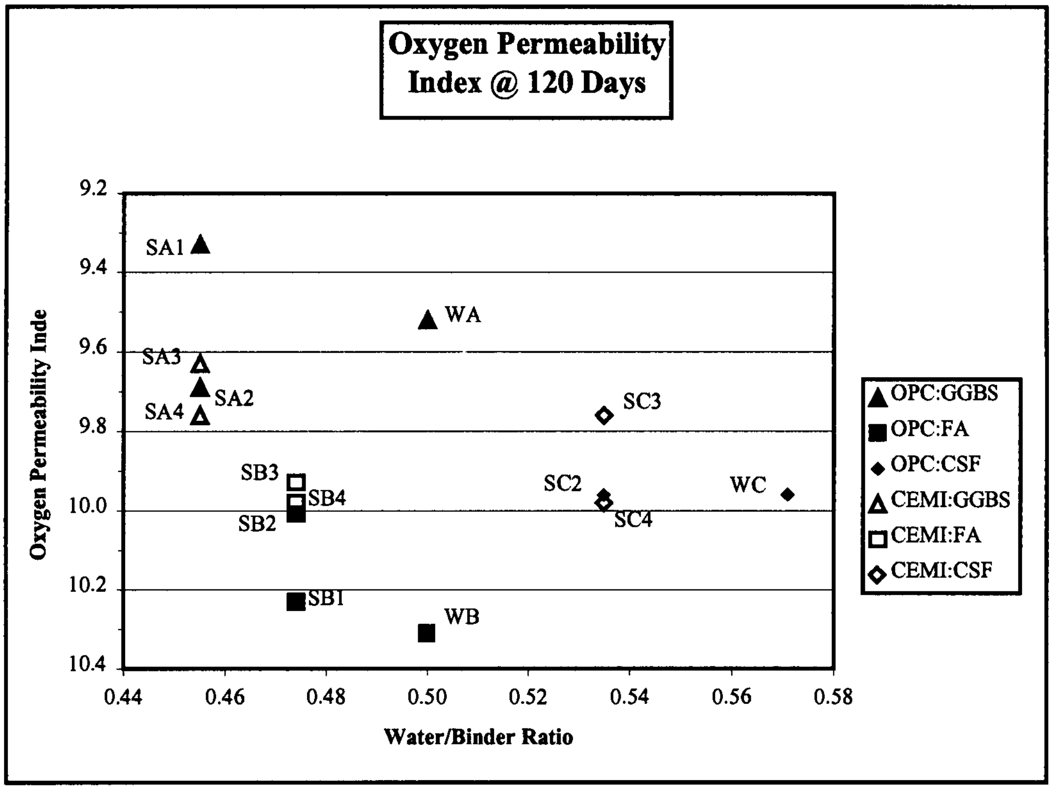


FIGURE 59: OXYGEN PERMEABILITY INDEX RESULTS AT 120 DAYS PLOTTED AGAINST WATER/BINDER RATIO FOR WET-CURED CUBES.

All of the concretes exhibit a spread of results rather than a distinct grouping related to the change in cement manufacture specification. Given the data presented here it is not possible to comment on the consistency of the trend noted at 28 days i.e. the OPC cement has the effect of increasing (i.e. improving) the oxygen permeability index. Notwithstanding this the oxygen permeability index results have generally increased, which indicates an improvement in oxygen permeability index with time.

For the slab series the OPC/GGBS concrete yields oxygen permeability index results in the range of 9,33 to 9,69. The OPC/FA concrete yields results in the range of 10,01 to 10,23 and the OPC/CSF concrete a result of 9,96. The OPC/FA concretes yield the highest (more favourable) oxygen permeability index results followed by OPC/CSF concretes (a change of ~ 45 % in k relative to OPC/FA). OPC/GGBS exhibit the lowest (poorer) results (a change of ~ 170 % in k relative to OPC/FA).

For the slab series the CEM I/GGBS concrete yields oxygen permeability index results in the range of 9,63 to 9,73. The CEM I/FA concrete yields results in the range of 9,93 to 9,98 and the CEM I/CSF concrete results in the range of 9,76 to 9,98. The CEM I/FA concrete yields the highest (more favourable) oxygen permeability index results followed by CEM I/CSF concretes (a change of ~ 20 % in k relative to CEM I/FA). CEM I/GGBS exhibit the lowest (poorer) results (a change of ~ 520 % in k relative to CEM I/FA).

For the wall series the OPC/GGBS concrete yields an oxygen permeability index of 9,52, OPC/FA concrete an oxygen permeability index of 10,31 and OPC/CSF concrete 9,96.

All the results for OPC/FA concrete fall inside the "Excellent" durability category, while the remainder of the results are inside the "Good" durability category. It must be noted however that the results for CEM I/FA are very close to the "Excellent" durability category as is the case for both OPC/CSF and CEM I/CSF concretes.

Ignoring the results for elements cast using CEM I cement and comparing the results for slabs and walls cast using OPC cement, does not yield any discernible trend given the scatter of results.

7.1.3 CONCLUSIONS RELATING TO THE INFLUENCE OF WATER/BINDER RATIO

Based on the observations and discussion, the following can be concluded:

- Change in water/binder ratio within the range of 0,46 to 0,57 has the effect of increasing the oxygen permeability index, as the ratio is reduced, for fully wet-cured samples with OPC cement at 28 days. At 120 days this trend is not sustained. In addition, the following trends were noted from the data in respect to binder type.
- The FA concretes exhibit marginally higher values of oxygen permeability index at 28 and 120 days when compared with CSF concretes, but exhibit substantially higher values when compared with GGBS concrete at both 28 and 120 days. The oxygen permeability index is markedly sensitive to cement extender type;
- The use of OPC cement resulted in slightly higher oxygen permeability index at 28 days, when compared with CEM I cements, however at 120 days this trend was not clearly defined.

These points are further amplified in the next section.

7.2 INFLUENCE OF BINDER TYPE

7.2.1 OXYGEN PERMEABILITY INDEX RESULTS AT 28 DAYS

Figure 60 shows the 28-day oxygen permeability index results for wet-cured cubes, plotted against the respective core compressive strengths for the three binder types.

In general the OPC cement concretes show improved (i.e. higher) oxygen permeability index results when compared to the CEM I cement concretes per cement extender type. The range in oxygen permeability index values is substantial over the range in compressive strengths shown, particularly for FA concretes. The influence of binder type is very pronounced in this case, exhibited by the large spread of results. FA and CSF concretes consistently produce more favourable oxygen permeability index results when compared to GGBS concretes used with both OPC and CEM I cement.

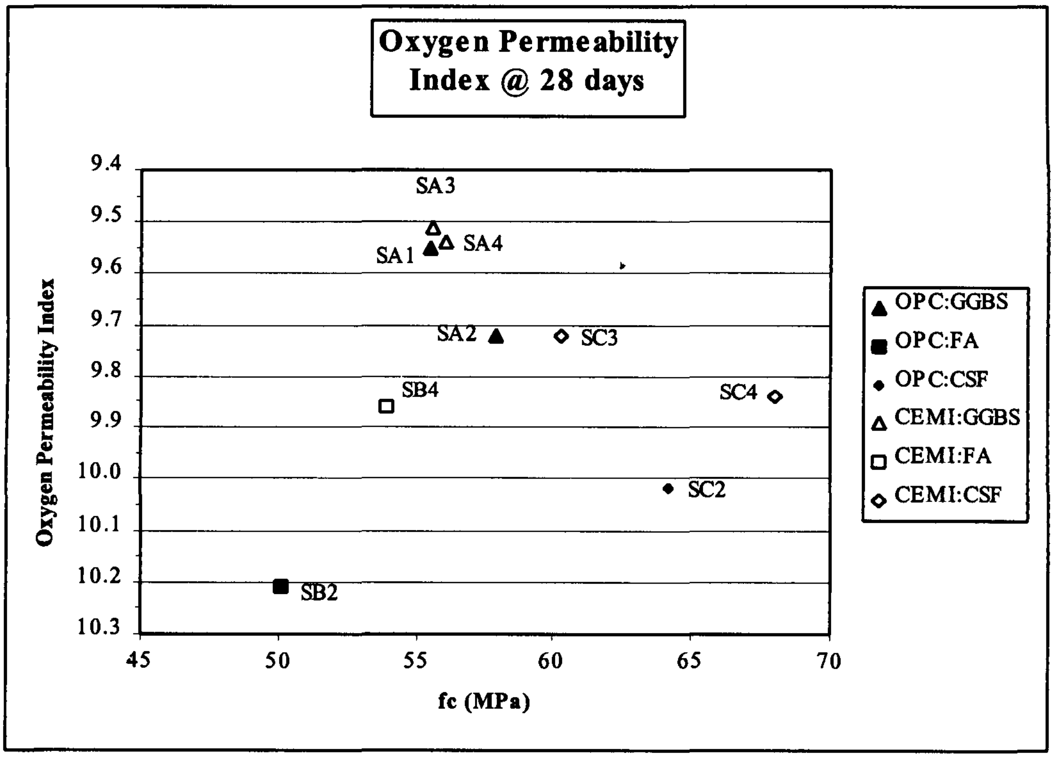


FIGURE 60: OXYGEN PERMEABILITY INDEX RESULTS AT 28 DAYS PLOTTED AGAINST 28-DAY COMPRESSIVE CORE STRENGTHS FOR WET-CURED CUBES.

7.2.2 OXYGEN PERMEABILITY INDEX RESULTS AT 120 DAYS

Figure 61 shows the 120-day oxygen permeability index results for wet-cured cubes, plotted against the respective core compressive strengths for the three binder types.

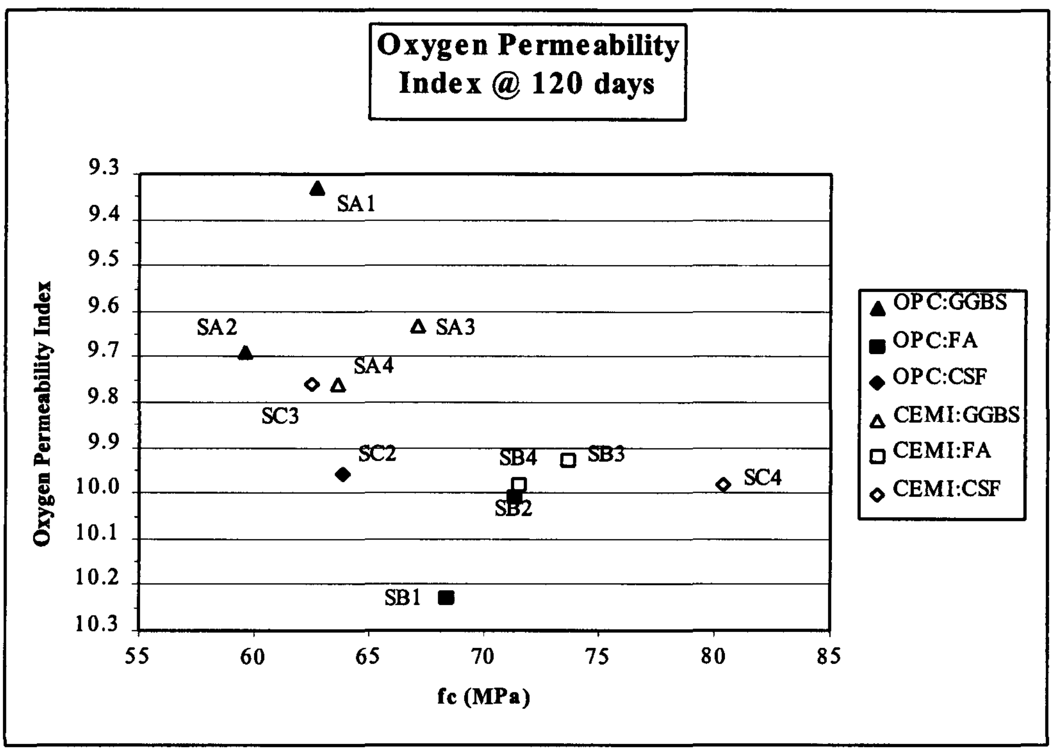


FIGURE 61: OXYGEN PERMEABILITY INDEX RESULTS AT 120 DAYS PLOTTED AGAINST 120-DAY COMPRESSIVE CORE STRENGTHS FOR WET-CURED CUBES.

No distinction is evident between the results for OPC and CEM I cement in this case. FA and CSF concretes consistently produce more favourable oxygen permeability index results when compared to GGBS concretes used with both OPC and CEM I cement.

7.2.3 CONCLUSIONS RELATING TO THE INFLUENCE OF BINDER TYPE

Based on the observations and discussion the following can be concluded:

- The influence of binder type is pronounced for well cured concretes in the strength ranges given at both 28 and 120 days;
- FA concretes consistently yielded the most favourable oxygen permeability index at 28 days followed by CSF concretes with a marginal reduction in durability properties. GGBS concretes however exhibited substantially poorer durability properties when compared with the FA concrete results;
- At 120 days the above trend is repeated in that FA concrete exhibits marginally more favourable oxygen permeability index results compared to CSF concretes while GGBS concretes exhibit noticeably poorer durability properties relative to FA and CSF concretes; and
- While OPC cement exhibited noticeably improved oxygen permeability index results compared with CEM I at 28 days.

7.3 INFLUENCE OF ELEMENT AGE

7.3.1 GGBS CONCRETES

Table 70 shows the change in oxygen permeability index with time for wet-cured concretes.

TABLE 70: OXYGEN PERMEABILITY INDEX RESULTS AT 28 AND 120 DAYS, FOR SLAB A SERIES.

ELEMENT	OXYGEN PERMEABILITY INDEX @ 28 DAYS	OXYGEN PERMEABILITY INDEX @ 120 DAYS
SLAB A1	9,55	9,33
SLAB A2	9,72	9,69
SLAB A3	9,51	9,63
SLAB A4	9,54	9,76

The oxygen permeability index reduces with element age for OPC cements and improves with age for CEM I cement. While the variation is small the trend is well established.

7.3.2 FA CONCRETES

Table 71 shows the change in oxygen permeability index with time for FA concretes.

TABLE 71: OXYGEN PERMEABILITY INDEX RESULTS AT 28 AND 120 DAYS, FOR SLAB B SERIES.

ELEMENT	OXYGEN PERMEABILITY INDEX @ 28 DAYS	OXYGEN PERMEABILITY INDEX @ 120 DAYS
SLAB B1	No data	10,23
SLAB B2	10,21	10,01
SLAB B3	No data	9,93
SLAB B4	9,86	9,98

The oxygen permeability index reduces with element age for OPC cements and improves with age for CEM I cement. While the variation is small the trend is well established.

7.3.3 CSF CONCRETES

Table 72 shows the change in oxygen permeability index with time for CSF concretes.

TABLE 72: OXYGEN PERMEABILITY INDEX RESULTS AT 28 AND 120 DAYS, FOR SLAB C SERIES.

ELEMENT	OXYGEN PERMEABILITY INDEX @ 28 DAYS	OXYGEN PERMEABILITY INDEX @ 120 DAYS
SLAB C1	No data	No data
SLAB C2	10,02	9,96
SLAB C3	9,72	9,76
SLAB C4	9,84	9,98

The oxygen permeability index reduces with element age for OPC cements and improves with age for CEM I cement. While the variation is small the trend is well established.

7.3.4 CONCLUSIONS RELATING TO THE INFLUENCE OF ELEMENT AGE

Based on the observations and discussion the following can be concluded:

- FA, GGBS and CSF concretes show a trend of oxygen permeability index increasing (more favourable) with time, when used with CEM I cement. When used with OPC cement the FA, GGBS and CSF concretes indicate a trend of reducing (less favourable) with time. This trend requires more investigation.

7.3.5 GENERAL CONCLUSIONS RELATING TO WET-CURED SAMPLES

Based on the observations and discussions in the preceding three sections of this chapter the following can be concluded, relative to fully wet-cured samples, and are considered the key findings for the first section of this chapter:

- The FA concretes produce the highest oxygen permeability index results at both 28 days and 120 days. The 28-day oxygen permeability index results are within the "Excellent" durability category for OPC cements, and "Good" durability category for CEM I cements. The oxygen permeability index results for this concrete exhibit the trend of improving in quality with time for CEM I cement, while the converse is true for OPC cements;

- The oxygen permeability index for CSF concrete exhibited a marginal reduction (poorer properties) in comparison to the FA concrete at 28 days, within the "Excellent" durability category for OPC cement slab series and the "Good" durability category for CEM I cement slab and wall series. At 120 days the oxygen permeability index results for CSF concrete have improved in quality and are still marginally lower than the FA concrete results for CEM I cements. At 120 days the oxygen permeability index for CSF concrete used with both OPC and CEM I cement falls within the "Good" durability category. As for FA concrete the oxygen permeability index results for this concrete exhibit the trend of improving in quality with time for CEM I cement, while the converse is true for OPC cements; and
- The GGBS concretes produce oxygen permeability index results markedly lower than the CSF or FA concrete at both 28 days and 120 days. The results are within the "Good" durability category for both OPC and CEM I cements at 28 days, with OPC cement yielding marginally lower oxygen permeability index results. At 120 days the oxygen permeability index is within the "Good" durability category for both OPC and CEM I cement, with no visible variation between the two cement types. The oxygen permeability index results for this concrete exhibit the trend of improving in quality with time for CEM I cement, while the converse is true for OPC cements.

7.4 INFLUENCE OF CURING METHOD

7.4.1 WALL SERIES

7.4.1.1 28-Day Results

Figure 62 shows the 28-day oxygen permeability index results for the three concretes (together with the environmental rating), with reference to the different curing methods.

From Figure 62, it is evident that as the environmental rating increases the oxygen permeability index increases. This observation is consistent for OPC/FA and OPC/CSF concretes and indicates that the oxygen permeability index is affected by curing. OPC/GGBS concretes show very little change, if any, with change in environmental rating.

The 28-day oxygen permeability index results for OPC/GGBS concretes are detailed in Table 73. The oxygen permeability index results for the OPC/GGBS fall broadly within the "Poor" and "Very Poor" durability category. Interestingly no curing yields the most favourable site cured result, in the "Poor" category, while the remainder of the site and wet curing yielded "Very Poor" result.

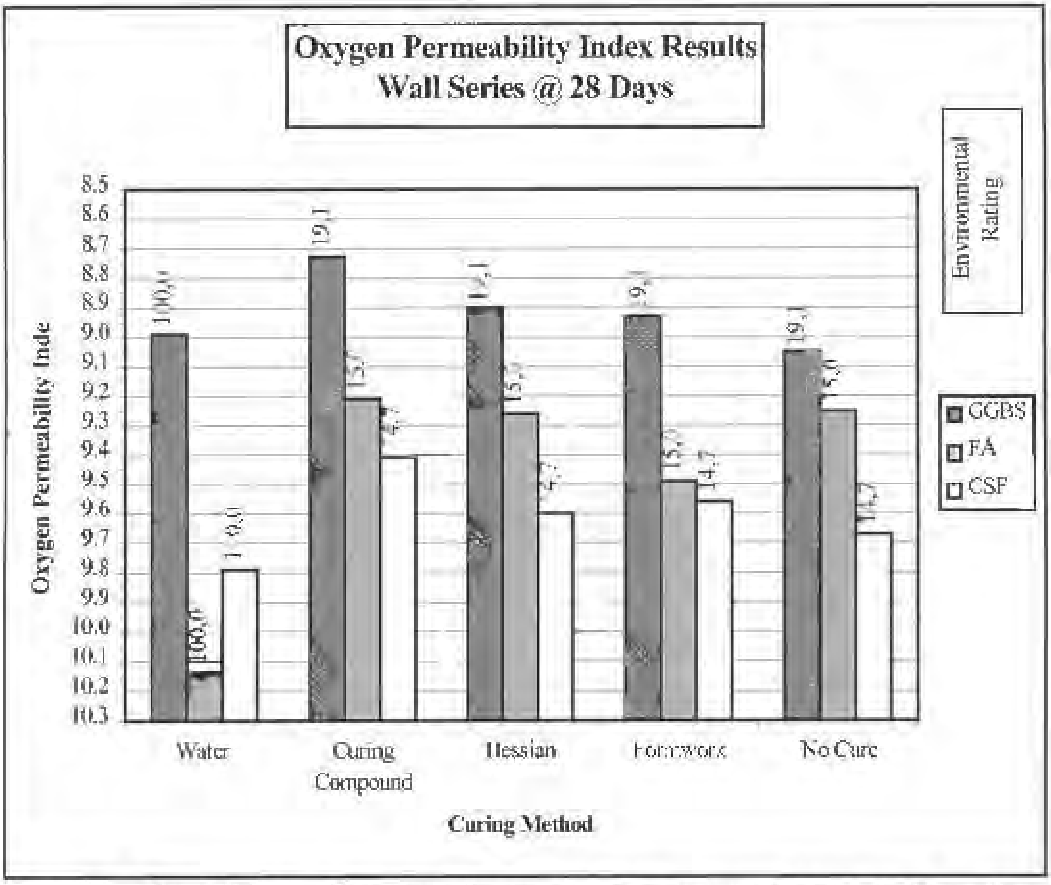


FIGURE 62: 28-DAY OXYGEN PERMEABILITY INDEX RESULTS FOR THE VARIOUS CONCRETES (TOGETHER WITH THE ENVIRONMENTAL RATING), WITH REFERENCE TO THE DIFFERENT CURING METHODS.

TABLE 73: 28-DAY OXYGEN PERMEABILITY INDEX RESULTS FOR OPC/GGBS CONCRETES PER CURING METHOD.

CURING METHOD	OXYGEN PERMEABILITY INDEX	CURING REDUCTION RATIO *
WATER	8,99	
COMPOUND	8,73	0,81
HESSIAN	8,90	0,23
FORMWORK	8,93	0,15
UNCURED	9,05	#

* Based on k

Nil or negative value

The 28-day oxygen permeability index results for OPC/FA concretes are detailed in Table 74.

TABLE 74: 28-DAY OXYGEN PERMEABILITY INDEX RESULTS FOR OPC/FA CONCRETES PER CURING METHOD.

CURING METHOD	OXYGEN PERMEABILITY INDEX	CURING REDUCTION RATIO *
WATER	10,14	
COMPOUND	9,21	7,51
HESSIAN	9,26	6,61
FORMWORK	9,49	3,51
UNCURED	9,25	6,78

* Based on k

For wet curing the oxygen permeability index results fall within the "Excellent" durability category while for the remaining site-cured samples, the oxygen permeability index falls within the "Poor" durability category.

The 28-day oxygen permeability index results for OPC/CSF concretes are detailed in Table 75.

TABLE 75: 28-DAY OXYGEN PERMEABILITY INDEX RESULTS FOR OPC/CSF CONCRETES PER CURING METHOD.

CURING METHOD	OXYGEN PERMEABILITY INDEX	CURING REDUCTION RATIO *
WATER	9,79	
COMPOUND	9,41	1,38
HESSIAN	9,60	0,55
FORMWORK	9,56	0,68
UNCURED	9,67	0,33

* Based on k

The oxygen permeability index results for the OPC/CSF concrete falls within the "Good" durability category, with the exception of the result for curing compound curing which falls in the "Poor" durability category.

For full-water curing OPC/FA concretes yielded the most favourable oxygen permeability index (10,14), followed by OPC/CSF concretes (9,79) and OPC/GGBS concretes (8,99).

For the site-curing methods the oxygen permeability index results for OPC/GGBS yield the least favourable results and fall into the "Very Poor" durability category, with curing compound curing exhibiting the poorest result. All of the site-curing results for the OPC/FA concretes are within the "Poor" durability category and the results for wet curing are in the "Excellent" category. The oxygen permeability index results for OPC/CSF fall broadly into the "Good" durability category.

Figure 63 shows the change (i.e. increase) in 28-day oxygen permeability results for the various curing methods, and different concretes. The figure uses a "curing reduction ratio" which is the difference between the oxygen permeability index under consideration (site-curing methods) and the fully water-cured condition divided by fully water-cured condition. It is in effect an indicator of the reduction in curing effectiveness of a given curing method, in relation to the fully water-cured condition. Thus the larger a particular "curing reduction ratio", the larger the shift between the fully cured oxygen permeability index value and the oxygen permeability index value for the site-curing method under consideration. **Note that the curing reduction ratio is based on the coefficient of permeability (k) and not the oxygen permeability index.**

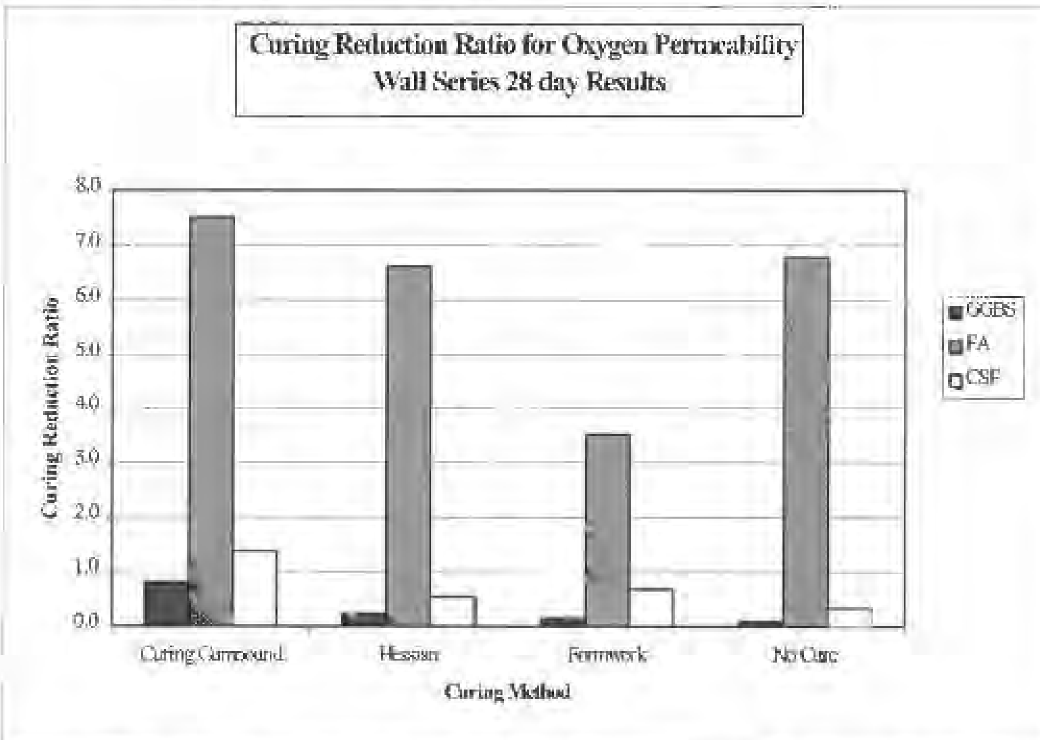


FIGURE 63: CHANGE IN 28-DAY OXYGEN PERMEABILITY RESULTS FOR WALL SERIES PLOTTED AGAINST RESPECTIVE CURING METHOD.

Figure 63, shows that the OPC/FA concretes exhibited the highest "curing reduction ratio" in oxygen permeability index per curing method. This is an indication of the sensitivity of the OPC/FA concrete to curing. The OPC/GGBS and OPC/CSF concretes yielded substantially lower "curing reduction ratio" values for the various curing methods. It must be noted however that the "curing reduction ratio" for OPC/GGBS concrete must be viewed with some trepidation, given that the result to wet curing is plausibly an outlier.

The OPC/FA concrete indicates that formwork curing is the most effective site-curing method followed by hessian curing, no active curing and the application of curing compound (in order of effectiveness). A substantial variation is evident between the "curing reduction ratio" for formwork curing and the other site-curing methods. For OPC/CSF concrete the ratio is remarkably consistent, with curing compound curing exhibiting a slightly higher ratio. It would thus appear that the OPC/CSF concrete exhibit very little sensitivity to the site-curing method utilised.

7.4.1.2 Conclusions Relating to 28-Day Results

Based on the observations and discussion and subject to the environmental conditions experienced by the elements, the following can be concluded:

- At 28 days the oxygen permeability index is affected by the curing method utilised;

- For the OPC/GGBS concretes the oxygen permeability index results at 28 days for all of the site-curing methods fall within the "Very Poor" durability category;
- For OPC/FA concretes the formwork curing yielded oxygen permeability index results at 28 days in the "Poor" durability category, while wet curing yield "Excellent" durability properties. The remainder of the site-curing methods yielded "Poor" 28-day durability properties;
- For OPC/CSF concretes the oxygen permeability index results at 28 days fall within the "Good" durability category, with the exception of curing compound curing which yielded "Poor" results;
- OPC/FA concretes exhibited the largest "curing reduction ratio" for each curing method, while OPC/GGBS and OPC/CSF concretes exhibited a substantially lower ratio for each curing method, hence reduced sensitivity to curing;
- Formwork retention as a curing method is more beneficial than no-curing for OPC/FA concretes, while for the OPC/GGBS and OPC/CSF concretes the application of curing compound was less beneficial than no curing. Wet curing offered clear benefits for OPC/FA, OPC/GGBS and OPC/CSF concretes.

7.4.1.3 120-Day Results

Figure 64 shows the 120-day oxygen permeability index results for the three concretes (together with the environmental rating), plotted against curing method. From Figure 64, it is evident that as the environmental rating increases the oxygen permeability index increases, per binder type, for all concrete types.

The 120-day oxygen permeability index results for OPC/GGBS concretes are detailed in Table 76.

Table 76: 120-Day Oxygen Permeability Index Results For OPC/GGBS Concretes Per Curing Method.

Curing Method	Oxygen Permeability Index	Curing Reduction Ratio *
Water	9,52	
Compound	9,04	2,06
Hessian	9,17	1,24
Formwork	8,80	4,35
Uncured	8,79	4,37

* Based on k

For wet curing, the oxygen permeability index results for the OPC/GGBS concrete falls within the "Good" durability category. For curing compound and hessian curing the oxygen permeability index falls within the "Poor" durability category while for formwork and no active curing the results fall within the "Very Poor" durability category.

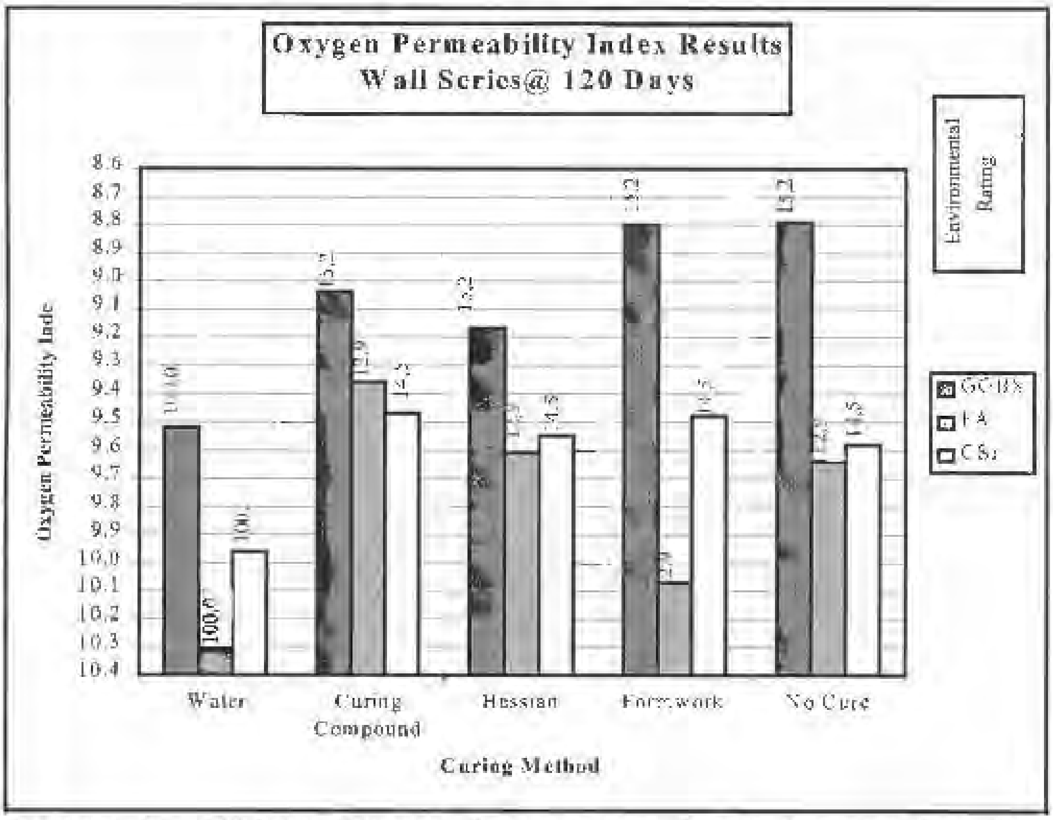


FIGURE 64: 120-DAY OXYGEN PERMEABILITY INDEX RESULTS FOR THE VARIOUS CONCRETES (TOGETHER WITH THE ENVIRONMENTAL RATING), WITH REFERENCE TO THE DIFFERENT CURING METHODS.

Considering the change in oxygen permeability index with time (using the 120-day data as a base) increases of ~ 90 % to ~ 100 % have occurred for the hessian and curing compound curing respectively, while for the water-cured cubes the increase is ~ 240%. For formwork and no active curing the oxygen permeability index has somewhat reduced (less favourable) with time. The various curing methods exhibit different effects on the oxygen permeability index with time, but in no instance do the improvements due to the site-curing match the continued improvements recorded for wet-cured concretes.

The 120-day oxygen permeability index results for OPC/FA concretes are detailed in Table 77.

TABLE 77: 120-DAY OXYGEN PERMEABILITY INDEX RESULTS FOR OPC/FA CONCRETES PER CURING METHOD.

CURING METHOD	OXYGEN PERMEABILITY INDEX	CURING REDUCTION RATIO *
WATER	10,31	
COMPOUND	9,36	7,90
HESSIAN	9,61	3,99
FORMWORK	10,07	0,74
UNCURED	9,64	3,64

* Based on k

For wet curing and formwork curing the oxygen permeability index falls within the "Excellent" durability category, while the results for hessian and no active curing falls in the "Good" durability category. For curing compound curing the results fall in the "Poor" durability category. Considering the change in oxygen permeability index (using the 120-day data as a base) increases of ~ 20 % to ~ 50 % occur for wet curing, curing compound curing and no curing. For hessian curing the change increases to ~ 120 % and for formwork curing ~ 280%.

The 120-day oxygen permeability index results for OPC/CSF concretes are detailed in Table 78.

TABLE 78: 120-DAY OXYGEN PERMEABILITY INDEX RESULTS FOR OPC/CSF CONCRETES PER CURING METHOD.

CURING METHOD	OXYGEN PERMEABILITY INDEX	CURING REDUCTION RATIO *
WATER	9,96	
COMPOUND	9,47	2,11
HESSIAN	9,55	1,59
FORMWORK	9,48	2,06
UNCURED	9,58	1,45

* Based on k

The oxygen permeability index results for OPC/CSF concrete falls within the "Good" durability category, for the wet curing, hessian and no curing. For formwork curing and the application of curing compound the results are within the "Poor" durability category. Considering the change in oxygen permeability index (using the 120-day data as a base) increases of ~ 20 % to ~ 50 % occur for wet and curing compound curing. For hessian curing, formwork curing and no active curing the oxygen permeability index test results decreased somewhat (less favourable) with time.

For wet curing OPC/FA concretes yielded the highest oxygen permeability index (10,31), followed by OPC/CSF concretes (9,96) and OPC/GGBS concretes (9,52).

Figure 65 shows the change in 120-day oxygen permeability results for the various curing methods, for the OPC/GGBS, OPC/FA and OPC/CSF concretes. The figure depicts the "curing reduction ratio" as discussed previously based on the coefficient of permeability (k).

Considering the data presented in Figure 65, OPC/CSF is the only concrete that exhibits reasonably consistent, relatively low "curing reduction ratios", indicating little sensitivity to site-curing. OPC/FA concrete exhibits a large variation in "curing reduction ratio", as does GGBS/OPC concrete. What is clearly indicated is the sensitivity of OPC/FA and OPC/GGBS concrete to curing, exhibited by the larger "curing reduction ratios", for some of the site cured conditions. OPC/FA concrete indicates that the application of curing compound is the least effective site-curing method, while no active curing and hessian curing are equally more effective with formwork curing the most effective. OPC/GGBS concrete indicated that formwork and no active curingwere equally least effective with application of curing compound and hessian curing equally more effective.

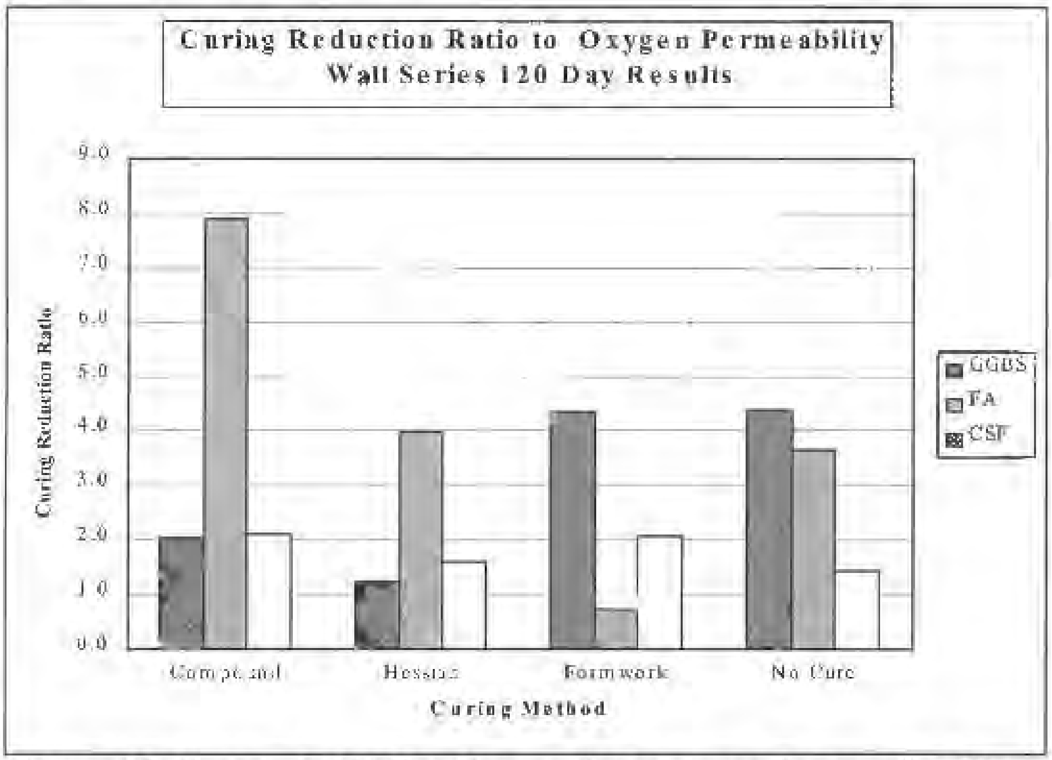


FIGURE 65: CHANGE IN 120-DAY OXYGEN PERMEABILITY RESULTS FOR WALL SERIES PLOTTED AGAINST RESPECTIVE CURING METHOD.

7.4.1.4 Conclusions Relating to 120-Day Results

Based on the observations and discussion the following can be concluded:

- At 120 days the oxygen permeability index is affected by the curing method utilised;
- For the OPC/GGBS concretes the oxygen permeability index results at 120 days for the site-curing methods falls within the "Poor" and "Very Poor" durability category, while full water-curing yields "Excellent" durability properties;
- For OPC/FA concretes full water curing yields oxygen permeability index results at 120 days in the "Excellent" durability category, while the results for the site-curing methods range from "Good" to "Poor";
- For OPC/CSF concretes the oxygen permeability index results at 120 days fall within the "Good" durability category;
- OPC/FA concretes exhibited the largest "curing reduction ratio" while OPC/CSF concretes exhibited a substantially lower ratio. OPC/GGBS concrete exhibited a noticeably larger ratio than OPC/CSF concrete, but lower than the largest peak for OPC/FA concrete.;
- Considering the "curing reduction ratio" for OPC/CSF concretes, it appears that it exhibits lower sensitivity to site-curing methods, within the context of the environmental exposure condition experienced; and
- The use of formwork retention as a curing method is more beneficial than no-curing for OPC/FA concretes, while for the OPC/GGBS concrete the use of a curing compound and hessian was more beneficial than no curing. Full wet curing offered clear benefits for OPC/FA, OPC/GGBS and OPC/CSF concretes.

- Note that, generally irrespective of curing method, FA concrete exhibited best performance followed by CSF and GGBS concrete, subject to the local climatic conditions.

7.4.1.5 General Conclusions Relating to Site Cured Wall Samples

Based on the observations and discussion the following can be concluded, relative to site cured wall samples. These are considered the key findings for this section of this chapter:

- OPC/GGBS concrete in walls exhibited definite sensitivity to curing at both 28 and 120 days. At 28 days the oxygen permeability index for various site-cured samples are within the "Very Poor" durability category, while at 120 days the results are within the "Very Poor" and "Good" durability category. No site-curing method emerges as being more beneficial than another at both 28 days and 120 days;
- OPC/FA concrete exhibited a substantial sensitivity to curing at both 28 and 120 days, and was the most sensitive of the three concretes used. At 28 days the oxygen permeability index for various site-cured samples are within the "Poor" durability category, while at 120 days the results are within the "Poor" to "Excellent" durability category. The use of formwork retention as curing method is more beneficial than no active curing at both 28 and 120 days. The application of curing compound and hessian curing is consistently less beneficial than no active curing at both 28 and 120 days; and
- OPC/CSF concrete exhibited the least sensitivity to curing at both 28 and 120 days, of the three concretes used. At 28 and 120 days the oxygen permeability index for various site-cured samples are within the "Poor" and "Good" durability category. At 28 and 120 days the order of efficiency of site-curing was consistent as follows; no curing, hessian curing, formwork retention and the application of curing compound (listed from most to least effective).

7.4.2 SLAB SERIES

7.4.2.1 28-Day Results

The data is discussed for the elements cast using OPC and CEM I separately. The slab series 1&2 were cast using OPC while series 3&4 were cast using CEM I.

7.4.2.2 Observations and Discussion: Series Cast Using OPC Concretes

Figure 66 shows the 28-day oxygen permeability index results for the three concretes (together with environmental rating), for the various curing methods.

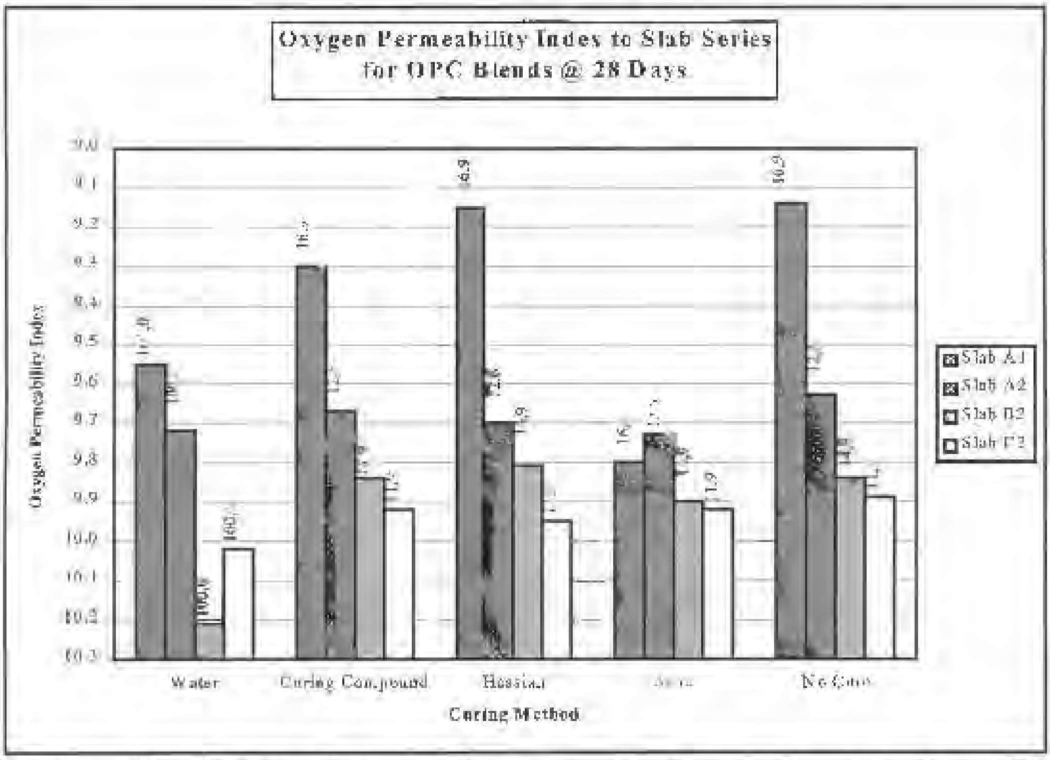


FIGURE 66: 28-DAY OXYGEN PERMEABILITY INDEX RESULTS FOR OPC CONCRETES (TOGETHER WITH THE ENVIRONMENTAL RATING), PLOTTED AGAINST VARIOUS CURING METHODS.

The 28-day oxygen permeability index results for the OPC/BBBS concrete are given in Table 79.

TABLE 79: 28-DAY OXYGEN PERMEABILITY INDEX RESULTS FOR OPC/GGBS CONCRETE PER CURING METHOD.

CURING METHOD	OXYGEN PERMEABILITY INDEX (SLAB A1 SERIES)	OXYGEN PERMEABILITY INDEX (SLAB A2 SERIES)	MEAN OXYGEN PERMEABILITY INDEX	MEAN CURING REDUCTION RATIO*
WATER	9,55	9,72	9,62	
COMPOUND	9,30	9,67	9,45	0,50
HESSIAN	9,15	9,70	9,34	0,92
SAND	9,80	9,73	9,76	#
UNCURED	9,14	9,63	9,32	1,02

* Based on k

\# Nil or negative value

Wet and sand curing are in the "Good" durability category while the application of curing compound, hessian and no active curing are in the "Poor" durability category. Sand curing is the most effective site curing method followed by the application of curing compound, hessian curing and no active curing (in order of effectiveness). It must be noted that in practical terms the variation in the results for the site curing methods is small and the results yield similar durability properties, except for sand curing which is clearly superior.

The 28-day oxygen permeability index results for the OPC/FA concrete are given in Table 80.

TABLE 80: 28-DAY OXYGEN PERMEABILITY INDEX RESULTS FOR OPC/FA CONCRETE PER CURING METHOD.

CURING METHOD	OXYGEN PERMEABILITY INDEX (SLAB B1 SERIES)	OXYGEN PERMEABILITY INDEX (SLAB B2 SERIES)	MEAN OXYGEN PERMEABILITY INDEX	MEAN CURING REDUCTION RATIO*
WATER	No data	10,21	10,21	
COMPOUND	No data	9,84	9,84	1,35
HESSIAN	No data	9,81	9,81	1,46
SAND	No data	9,90	9,90	1,01
UNCURED	No data	9,84	9,84	1,34

* Based on k

The result for wet curing is in the "Excellent" durability category, while the site cured results are all within the "Good" durability category, with hessian curing yielding the lowest result (poorest properties), by a small margin. This re-iterates the previous finding of the sensitivity of the OPC/FA concrete to curing. Sand curing is the most effective site curing method followed by the application of curing compound, no active curing and hessian (in order of effectiveness). It must be noted that in practical terms the variations noted between the site cured results are small and yield effectively similar results.

The 28-day oxygen permeability index results for the OPC/CSF concrete are given in Table 81.

TABLE 81: 28-DAY OXYGEN PERMEABILITY INDEX RESULTS FOR OPC/CSF CONCRETE PER CURING METHOD.

CURING METHOD	OXYGEN PERMEABILITY INDEX (SLAB C1 SERIES)	OXYGEN PERMEABILITY INDEX (SLAB C2 SERIES)	MEAN OXYGEN PERMEABILITY INDEX	MEAN CURING REDUCTION RATIO*
WATER	No data	10,02	10,02	
COMPOUND	No data	9,92	9,92	0,26
HESSIAN	No data	(Outlier)	No data	No data
SAND	No data	9,92	9,92	0,23
UNCURED	No data	9,89	9,89	0,32

* Based on k

The result for wet curing is within the "Excellent" durability category, and the site cured results are all within the "Good" durability category. Sand curing is the most effective site curing method followed by the application of curing compound and no active curing (in order of effectiveness). Once again it must be noted that the variation between the various site cured results is very small.

Figure 67 shows the mean change in 28-day oxygen permeability results for the various curing methods, for different concretes, and is based on mean curing reduction ratio as presented in Tables 79 through 81.

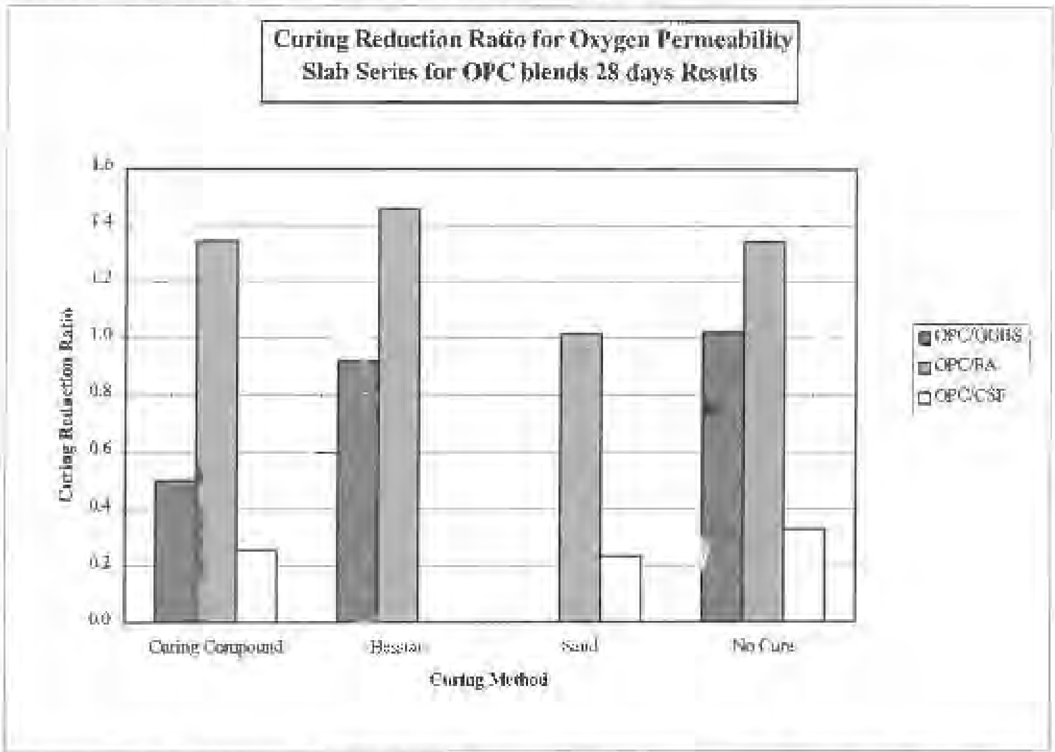


FIGURE 67: CHANGE IN 28-DAY OXYGEN PERMEABILITY RESULTS FOR SLAB SERIES CAST USING OPC, PLOTTED AGAINST RESPECTIVE CURING METHOD.

OPC/GGBS and OPC/FA concretes exhibited the highest "curing reduction ratio" in comparison with OPC/CSF concrete, indicating the sensitivity of these concretes to curing.

For OPC/GGBS concrete sand curing is shown to be the most effective site curing method, followed by the application of curing compound, hessian and no active curing with an equal marginally reduces effectiveness. OPC/FA concrete indicates that sand curing is the most effective site curing method followed by no active curing, hessian and the application of curing compound curing all exhibiting similar effectiveness. For OPC/CSF concrete no site curing method indicates an improved effectiveness relative to another.

7.4.2.3 Observations and Discussion: Series Cast Using CEM I Concretes

Figure 68 shows the 28-day oxygen permeability index results for the three concretes (together with environmental rating), with reference to the curing methods.

The 28-day oxygen permeability index results for the CEM I/GGBS concrete are given in Table 82.

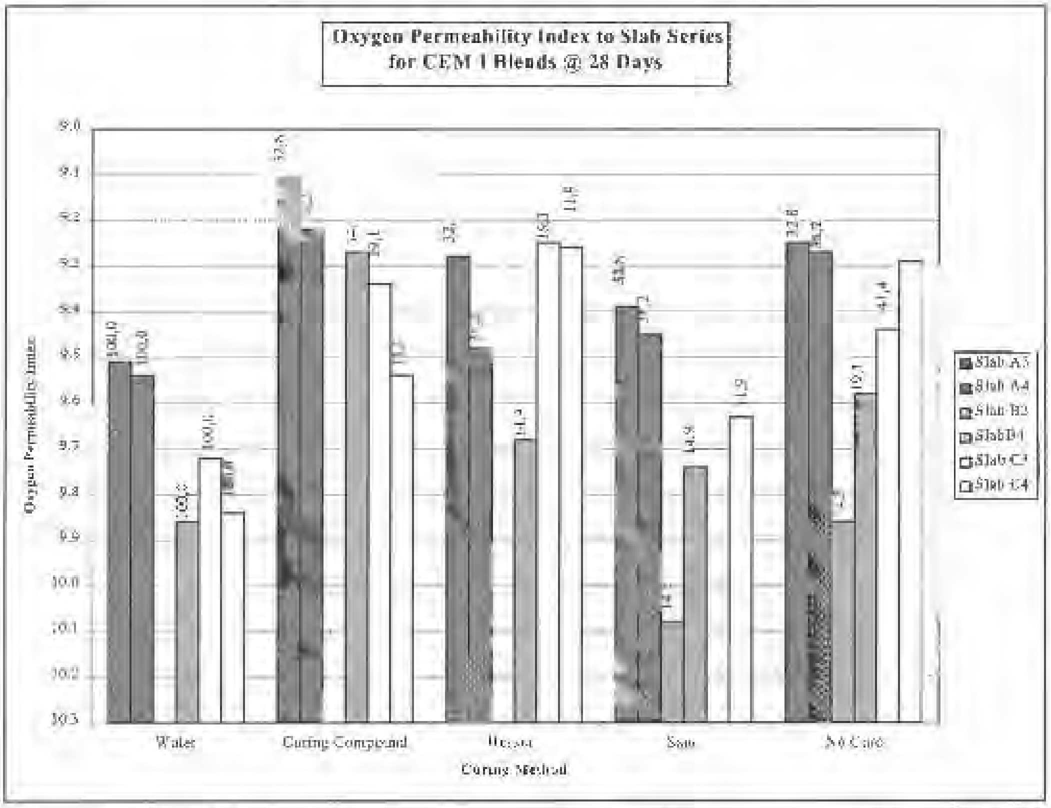


FIGURE 68: 28-DAY OXYGEN PERMEABILITY INDEX RESULTS FOR CEM I CONCRETES (TOGETHER WITH THE ENVIRONMENTAL RATING), PLOTTED AGAINST VARIOUS CURING METHODS.

TABLE 82: 28-DAY OXYGEN PERMEABILITY INDEX RESULTS FOR CEM I/GGBS CONCRETE PER CURING METHOD.

CURING METHOD	OXYGEN PERMEABILITY INDEX (SLAB A3 SERIES)	OXYGEN PERMEABILITY INDEX (SLAB A4 SERIES)	MEAN OXYGEN PERMEABILITY INDEX	MEAN CURING REDUCTION RATIO *
WATER	9,51	9,54	9,52	
COMPOUND	9,11	9,22	9,16	1,31
HESSIAN	9,28	9,48	9,37	0,44
SAND	9,39	9,45	9,42	0,26
UNCURED	9,25	9,27	9,26	0,84

* Based on k

The results for wet curing are within the "Good" durability category, while the remainder of the results are within the "Poor" durability category, with the application of curing compound yielding the lowest (poorest) result. Sand curing is the most effective site curing method followed by hessian curing, no active curing and the application of curing compound (in order of effectiveness). The variation in results between the various site cured concretes is not negligible in this case, and sand curing is superior to curing compound curing.

The change in cement type has had no noticeable effect on the results and when compared to the OPC cement data set, at the same element age, the results are "indistinguishable". Also of interest is that when compared with the OPC cement data set, sand curing has retained the same curing efficiency ranking.

The 28-day oxygen permeability index results for the CEM I/FA concretes are given in Table 83.

TABLE 83: 28-DAY OXYGEN PERMEABILITY INDEX RESULTS FOR CEM I/FA CONCRETE PER CURING METHOD.

CURING METHOD	OXYGEN PERMEABILITY INDEX (SLAB B3 SERIES)	OXYGEN PERMEABILITY INDEX (SLAB B4 SERIES)	MEAN OXYGEN PERMEABILITY INDEX	MEAN CURING REDUCTION RATIO *
WATER	No data	9,86	9,86	
COMPOUND	No data	9,27	9,27	2,83
HESSIAN	No data	9,68	9,68	0,50
SAND	10,08	9,74	9,88	#
UNCURED	9,86	(Outlier)	9,86	#

* Based on k

\# Nil or negative value

The results for full wet curing are within the "Good" durability category as are all the site cured results, with the exception of the application of curing compound, which is within the "Poor" durability category. Sand curing is the most effective site curing method followed by no active curing, hessian curing and the application of curing compound (in order of effectiveness). The variation in results between the various site cured concretes is not, and sand curing is superior to curing compound curing.

The change in cement type has had no noticeable effect on the results and when compared to the OPC cement data set, at the same element age, the results are "indistinguishable".

The 28-day oxygen permeability index results for the CEM I/CSF concrete are given in Table 84.

TABLE 84: 28-DAY OXYGEN PERMEABILITY INDEX RESULTS FOR CEM I/CSF CONCRETE PER CURING METHOD.

CURING METHOD	OXYGEN PERMEABILITY INDEX (SLAB C3 SERIES)	OXYGEN PERMEABILITY INDEX (SLAB C4 SERIES)	MEAN OXYGEN PERMEABILITY INDEX	MEAN CURING REDUCTION RATIO *
WATER	9,72	9,84	9,78	
COMPOUND	9,34	9,54	9,42	1,26
HESSIAN	9,25	9,26	9,26	2,34
SAND	No data	9,63	9,63	0,40
UNCURED	9,44	9,29	9,36	1,63

* Based on k

The results for wet and sand curing are within the "Good" durability category, while the remainder of the results are within the "Poor" durability category, with hessian curing yielding the lowest (poorest) result. Sand curing is the most effective site curing method followed by the application of curing compound, no active curing and hessian curing (in order of effectiveness). Except for sand curing, there is little practical difference between the site cured results. When these results are compared to the OPC results, at the same element age, it is noted that generally the use of CEM I cement yields noticeably lower, i.e. less favourable, oxygen permeability index results.

Figure 69 shows the mean change in 28-day oxygen permeability index results for the various curing methods, for the different concretes and is based on mean curing reduction ratio as presented in Tables 77 through 79.

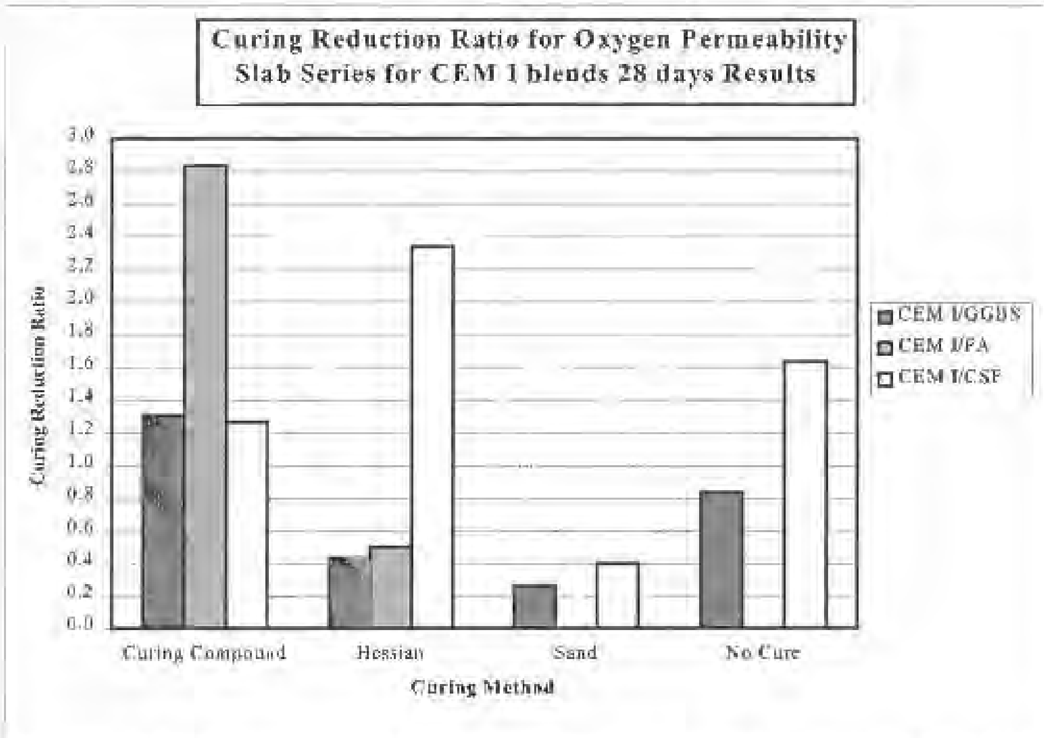


FIGURE 69: CHANGE IN 28-DAY OXYGEN PERMEABILITY RESULTS FOR SLAB SERIES CAST USING CEM I, PLOTTED AGAINST RESPECTIVE CURING METHOD.

For CEM I/GGBS concrete, sand and hessian curing are equally effective followed by no active curing and the application of curing compound (in order of effectiveness). CEM I/FA concrete shows that sand and hessian curing are more effective than the application of curing compound. For CEM I/CSF concrete sand curing is more effective than the application of curing compound, no active curing and hessian curing (in order of effectiveness).

When the data presented here are compared with the OPC cement data, at the same element age, it is noted that for GGBS concrete the "curing reduction ratio" has reduced for hessian, sand and no active curing but increased for the application of curing compound. For FA concrete the ratio has reduced for hessian curing but increased for the application of curing compound curing. For CSF concrete the "curing reduction ratio" has increased for all the site curing methods.

7.4.2.4 Conclusions Relating to 28-Day Results

Based on the observation and discussion and subject to the environmental conditions experienced, the following can be concluded:

- GGBS concrete in slabs exhibited definite sensitivity to curing at 28 days for both OPC and CEM I cements. The oxygen permeability index results for the various site-cured samples are within the "Good" and "Poor" durability category for OPC cement, and "Poor" durability category for CEM I cement. The use of CEM I cement with GGBS has had no noticeable effect on the oxygen permeability index when compared to OPC cement. Sand curing is more beneficial than the application of curing compound, hessian curing or no active curing (in order of effectiveness) for OPC/GGBS concretes at 28 days. For the CEM I/GGBS concrete at 28 days sand and hessian curing are more effective than no active curing or the application of curing compound (in order of effectiveness);
- FA concrete in slabs exhibited definite sensitivity to curing at 28 days for OPC and CEM I cements. The oxygen permeability index results for the various site-cured samples are within the "Good" durability category for OPC cement, and "Good" and "Poor" durability category for CEM I cement. The use of CEM I cement with FA has had no noticeable effect on the oxygen permeability index when compared to OPC cement. Sand curing is more beneficial than the application of curing compound, no active curing or hessian curing (in order of effectiveness) for OPC/FA concretes at 28 days. For the CEM I concrete at 28 days sand curing more beneficial than no active curing, hessian curing and the application of curing compound (in order of effectiveness);
- CSF concrete in slabs exhibited definite sensitivity to curing at 28 days for OPC and CEM I cements. The oxygen permeability index for the various site-cured samples are within the "Good" durability category for OPC cement, and "Good" and "Poor" durability category for CEM I cement. The use of CEM I cement with CSF has resulted in a noticeable reduction (poorer properties) in oxygen permeability index results when compared to OPC cement. Sand curing is more beneficial than the application of curing compound or no active curing (in order of effectiveness) for OPC/GGBS concretes at 28 days. For the CEM I/CSF concrete at 28 days sand curing is more beneficial than the application of curing compound, no active curing or hessian curing; and
- GGBS and FA concrete when used with OPC cement exhibited a marked sensitivity to curing compared to OPC/CSF concrete. For CEM I cement however GGBS and FA concretes did not exhibit this trend while CSF concrete showed an increase in curing sensitivity.
- Sand curing is consistently superior to the other site curing methods for all the binder types.

7.4.3 SLAB SERIES

7.4.3.1 120-Day Results

The data is discussed for the elements cast using OPC and CEM I separately. The slab series 1&2 were cast using OPC while series 3&4 were cast using CEM I.

7.4.3.2 Observations and Discussion: Series Cast Using OPC Concretes

Figure 70 shows the 120-day oxygen permeability index results for the three concretes (together with environmental rating), for to the different curing methods.

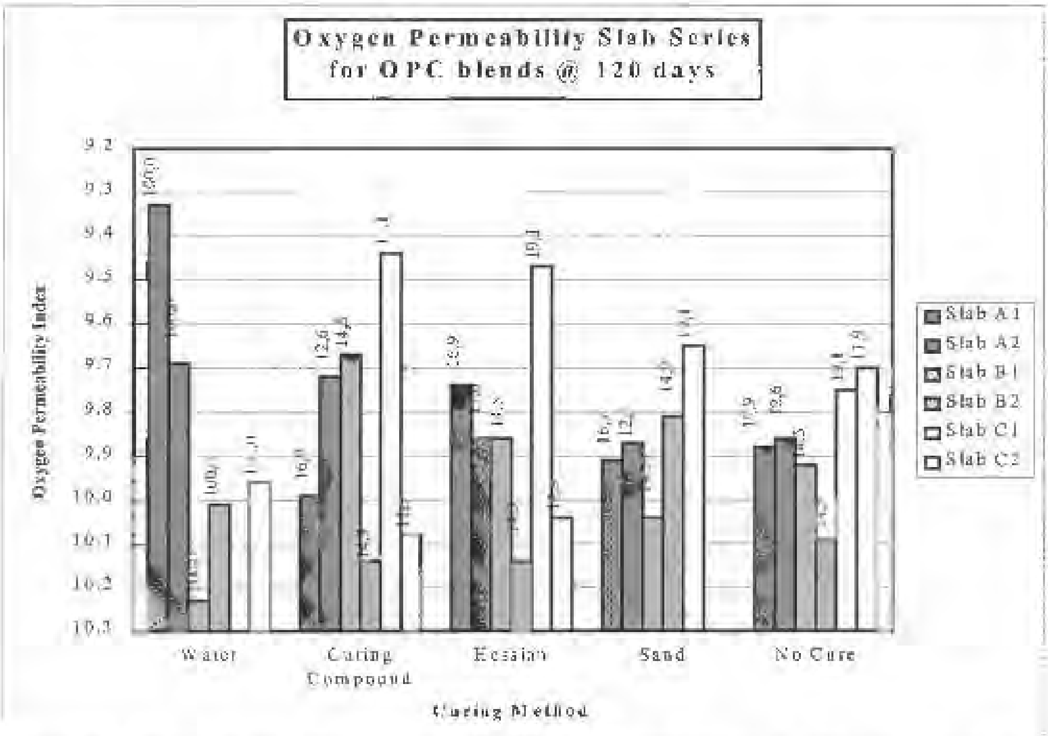


FIGURE 70: 120-DAY OXYGEN PERMEABILITY INDEX RESULTS FOR OPC CONCRETES (TOGETHER WITH THE ENVIRONMENTAL RATING), PLOTTED AGAINST VARIOUS CURING METHODS.

The 120-day oxygen permeability index results for the OPC/GGBS concrete are given in Table 85.

TABLE 85: 120-DAY OXYGEN PERMEABILITY INDEX RESULTS FOR OPC/GGBS CONCRETE PER CURING METHOD.

CURING METHOD	OXYGEN PERMEABILITY INDEX (SLAB A1 SERIES)	OXYGEN PERMEABILITY INDEX (SLAB A2 SERIES)	MEAN OXYGEN PERMEABILITY INDEX	MEAN CURING REDUCTION RATIO *
WATER	9,33	9,69	9,48	
COMPOUND	9,99	9,72	9,83	#
HESSIAN	9,74	9,86	9,80	#
SAND	9,91	9,87	9,89	#
UNCURED	9,88	9,86	9,87	#

* Based on k

\# Nil or negative value

The result for wet curing, while shown to be statistically acceptable, is somewhat questionable. All the site cured results are markedly similar and fall in a narrow band, inside the "Good" durability category, while wet curing falls inside the "Poor" category. Sand curing is the most effective site curing method followed by no active curing, the application of curing compound and no active curing (in order of effectiveness). It must be noted that the variation between the results for the site curing methods are small in real terms and all of the results are within the "Good" durability category. The change in oxygen permeability index results, relative to the 28-day results, using the 120-day results as a base, indicate that no active curing shows the largest change and the application of curing compound the least.

The 120-day oxygen permeability index results for the OPC/FA concretes are given in Table 86.

TABLE 86: 120-DAY OXYGEN PERMEABILITY INDEX RESULTS FOR OPC/FA CONCRETE PER CURING METHOD.

CURING METHOD	OXYGEN PERMEABILITY INDEX (SLAB B1 SERIES)	OXYGEN PERMEABILITY INDEX (SLAB B2 SERIES)	MEAN OXYGEN PERMEABILITY INDEX	MEAN CURING REDUCTION RATIO *
WATER	10,23	10,01	10,11	
COMPOUND	9,67	10,14	9,85	0,82
HESSIAN	9,86	10,14	9,98	0,33
SAND	10,04	9,81	9,91	0,58
UNCURED	9,92	10,09	10,00	0,29

* Based on k

The results for wet curing and no active curing are inside the "Excellent" durability category, while the remainder of the site cured results are within the "Good" durability category, with the application of curing compound yielding the lowest result (poorest properties). In practical terms, the site cured results are similar except for the poorer curing compound results. The change in oxygen permeability index results, relative to the 28-day results, indicate that the oxygen permeability index at 120 days reduces (develops poorer properties) for wet curing while no active curing exhibits the largest change and sand curing the least.

The 120-day oxygen permeability index results for the OPC/CSF concretes are given in Table 87.

TABLE 87: 120-DAY OXYGEN PERMEABILITY INDEX RESULTS FOR OPC/CSF CONCRETE PER CURING METHOD.

CURING METHOD	OXYGEN PERMEABILITY INDEX (SLAB C1 SERIES)	OXYGEN PERMEABILITY INDEX (SLAB C2 SERIES)	MEAN OXYGEN PERMEABILITY INDEX	MEAN CURING REDUCTION RATIO *
WATER	No data	9,96	9,96	
COMPOUND	9,44	10,08	9,65	1,02
HESSIAN	9,47	10,04	9,67	0,95
SAND	9,65	(Outlier)	9,65	1,03
UNCURED	9,75	9,70	9,72	0,72

* Based on k

The results fall within a narrow band in the "Good" durability category. In practical terms, all of the site curing methods achieve similar results. The change in oxygen permeability index results, relative to the 28-day results, using the 120-day results as a base, indicate that the application of curing compound shows the largest change and sand curing the least.

Figure 71 shows the mean change in 120-day oxygen permeability results for the various curing methods for different concretes, and is based on mean curing reduction ratios as presented in Tables 80 through 82.

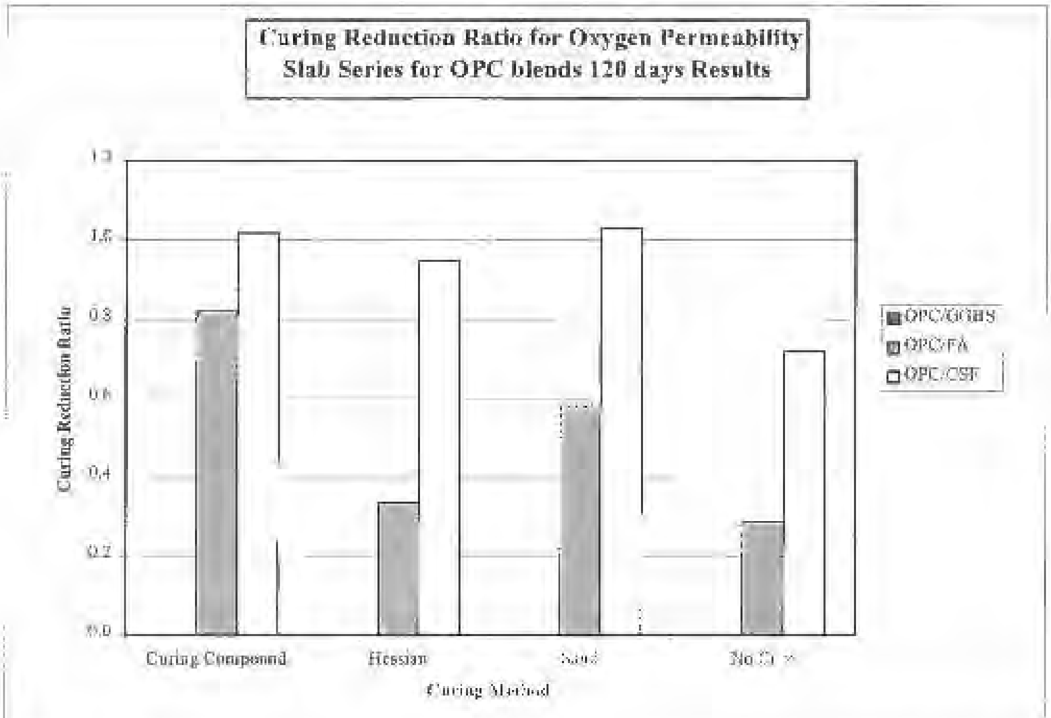


FIGURE 71: CHANGE IN 120-DAY OXYGEN PERMEABILITY RESULTS FOR SLAB SERIES CAST USING OPC, PLOTTED AGAINST RESPECTIVE CURING METHOD.

OPC/CSF concrete exhibited the highest "curing reduction ratio" in comparison with OPC/FA concrete.

As noted earlier all the site curing methods produced similar results, in practical terms, with curing compound curing proving on balance to be the least effective curing method.

The "curing reduction ratio" for OPC/FA concrete has reduced from 1,0 to 1,5 at 28 days to 0,3 to 0,8 at 120 days. For OPC/CSF concrete the "curing reduction ratio" has increased from 0,2 to 0,3 at 28 days to 0,7 to 1,0 at 120 days.

7.4.3.3 Observations and Discussion: Series Cast Using CEM I Concretes

Figure 72 shows the 120-day oxygen permeability index results for the three concretes (together with environmental rating), with reference to the curing methods.

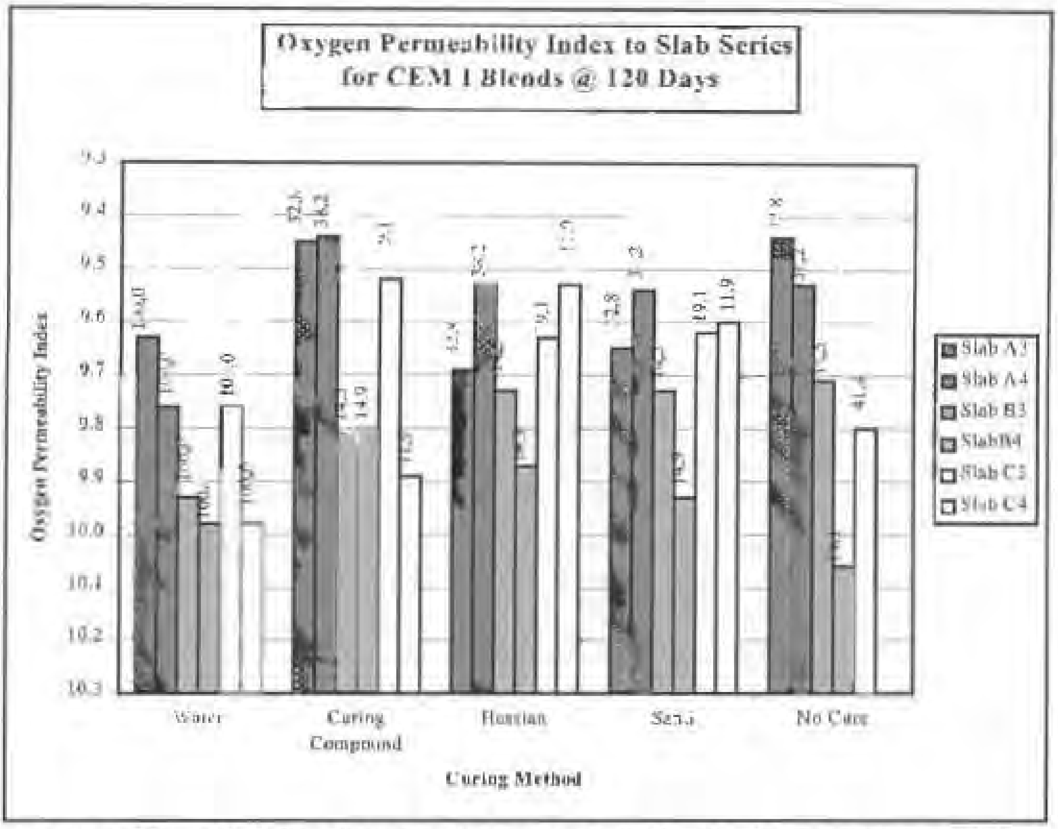


FIGURE 72: 120-DAY OXYGEN PERMEABILITY INDEX RESULTS FOR CEM I CONCRETES (TOGETHER WITH THE ENVIRONMENTAL RATING), PLOTTED AGAINST VARIOUS CURING METHODS.

The 120-day oxygen permeability index results for the CEM I/GGBS concretes are given in Table 88.

TABLE 88: 120-DAY OXYGEN PERMEABILITY INDEX RESULTS FOR CEM I/GGBS CONCRETE PER CURING METHOD.

CURING METHOD	OXYGEN PERMEABILITY INDEX (SLAB A3 SERIES)	OXYGEN PERMEABILITY INDEX (SLAB A4 SERIES)	MEAN OXYGEN PERMEABILITY INDEX	MEAN CURING REDUCTION RATIO *
WATER	9,63	9,76	9,69	
COMPOUND	9,45	9,44	9,44	0,77
HESSIAN	9,69	9,53	9,60	0,22
SAND	9,65	9,54	9,59	0,26
UNCURED	9,44	9,53	9,49	0,61

* Based on k

The results for wet curing, hessian curing and sand curing are within the "Good" durability category, while the remainder of the results are within the "Poor" durability category, with the application of curing compound yielding the lowest (poorest) result. Hessian curing is the most effective site curing method followed by sand curing, no active curing and the application of curing compound (in order of effectiveness).

When these results are compared to the OPC results, at the same element age, it is noted that generally the use of CEM I cement results in lower, i.e. less favourable, oxygen permeability index results.

The 120-day oxygen permeability index results for the CEM I/FA concretes are given in Table 89.

Table 89: 120-Day Oxygen Permeability Index Results For CEM I/FA Concrete Per Curing Method.

Curing Method	Oxygen Permeability Index (Slab B3 Series)	Oxygen Permeability Index (Slab B4 Series)	Mean Oxygen Permeability Index	Mean Curing Reduction Ratio *
Water	9,93	9,98	9,95	
Compound	9,81	9,80	9,81	0,41
Hessian	9,73	9,87	9,79	0,45
Sand	9,73	9,93	9,82	0,36
Uncured	9,71	10,06	9,85	0,28

* Based on k

All of the results are within the "Good" durability category. In practical terms all the site curing methods yield similar results. When these results are compared to the OPC results, at the same element age, it is noted that generally the use of CEM I cement results in lower, i.e. less favourable, oxygen permeability index results.

The 120-day oxygen permeability index results for the CEM I/CSF concrete are given in Table 90.

Table 90: 120-Day Oxygen Permeability Index Results For CEM I/CSF Concrete Per Curing Method.

Curing Method	Oxygen Permeability Index (Slab C3 Series)	Oxygen Permeability Index (Slab C4 Series)	Mean Oxygen Permeability Index	Mean Curing Reduction Ratio *
Water	9,76	9,98	9,86	
Compound	9,52	9,89	9,66	0,57
Hessian	9,63	9,53	9,57	0,93
Sand	9,62	9,60	9,61	0,77
Uncured	9,80	No data	9,80	0,16

* Based on k

All the results are within the "Good" durability category. No active curing is the most effective site curing method followed by the application of curing compound, sand curing and hessian curing (in order of effectiveness). When these results are compared to the OPC results, at the same element age, it is noted that generally the use of CEM I cement results in lower i.e. less favourable oxygen permeability index results.

Figure 73 shows the mean change in 120-day oxygen permeability results for the various curing methods, for the different concretes and is based on mean curing reduction ratios as presented in Tables 83 through 85.

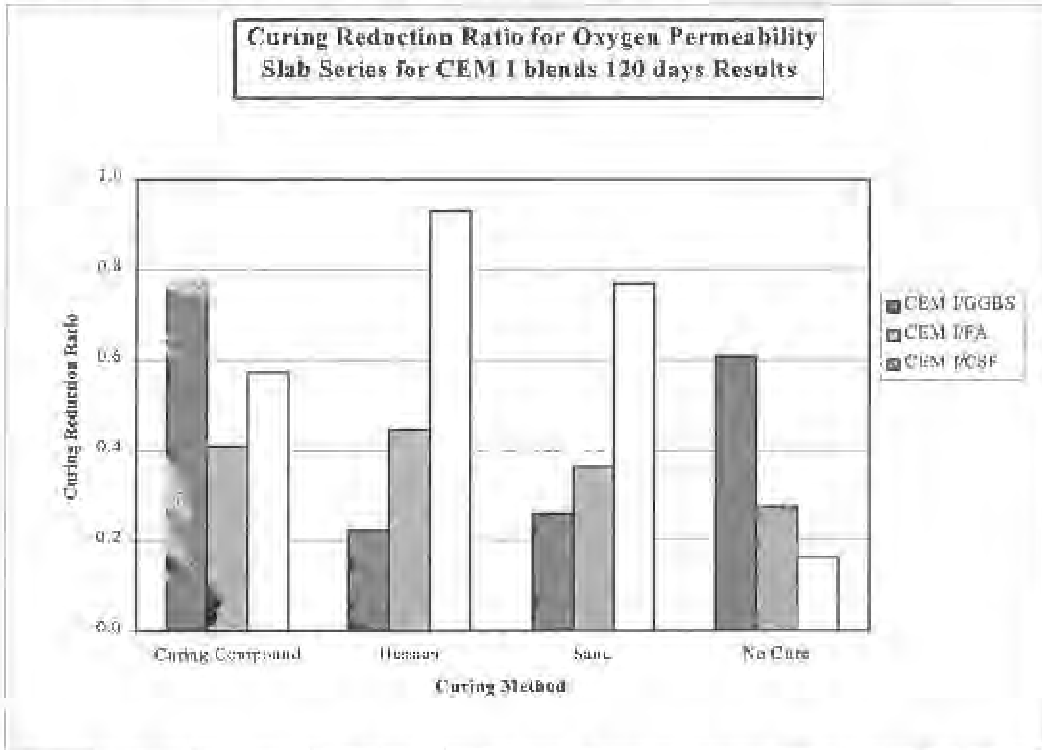


FIGURE 73: CHANGE IN 120-DAY OXYGEN PERMEABILITY RESULTS FOR SLAB SERIES CAST USING CEM I, PLOTTED AGAINST RESPECTIVE CURING METHOD.

No concrete indicates a notable increase in curing sensitivity relative to another and variations are noted across the range of site cured results.

While there are internal variations between the effectiveness of the site curing methods, for the various binder types at 120 days, there is usually little practical difference between the site curing methods.

The "curing reduction ratio" for CEM I/GGBS concrete has remained unchanged from 0,3 to 1,3 at 28 days to 0,2 to 1,3 at 120 days. For CEM I/FA concrete however the ratio has reduced notably from 0,5 to 2,8 at 28 days to 0,3 to 0,5 at 120 days. CEM I/CSF concrete also exhibits a reduction in "curing reduction ratio" from 0,4 to 2,4 at 28 days to 0,2 to 0,9 at 120 days.

When compared with the OPC concretes at 120 days it is interesting to note that the curing reduction ratio for GGBS and CSF concretes (cast using CEM I) are very similar to the OPC concretes.

7.4.3.4 Conclusions Relating to 120-Day Results

Based on the observation and discussion, and subject to the environmental conditions experienced, the following can be concluded:

- GGBS concrete in slabs exhibited definite sensitivity to curing at 120 days for OPC and CEM I cements. The oxygen permeability index for the various site-cured samples is within the "Good" durability category for OPC cement and spread between the "Good" and "Poor" durability categories for CEM I cement. The use of CEM I cement with GGBS results in a noticeable reduction in oxygen permeability index when compared to OPC cement. The various site cured concrete exhibit effectively similar results and no active curing method emerges as more effective than another; and

- FA concrete in slabs exhibited definite sensitivity to curing at 120 days for OPC and CEM I cements. The oxygen permeability index for the various site-cured samples is within the "Good" durability category for both OPC and CEM I cement. The use of CEM I cement with FA results in a marginal reduction in oxygen permeability index results when compared to OPC cement. The various site cured concrete exhibit effectively similar results and no active curing method emerges as more effective than another; and
- CSF concrete in slabs exhibited definite sensitivity to curing at 120 days for OPC and CEM I cements. The oxygen permeability index for the various site-cured samples is within the "Excellent" to "Good" durability category for OPC cement and in the "Good" durability categories for CEM I cement. The various site cured concrete exhibit effectively similar results and no active curing method emerges as more effective than another; and
- Notwithstanding the trend that the site curing methods yield similar result, the effect of wet curing is well established and produces more favourable results for all the binder types.

7.4.3.5 General Conclusions Relating to Site Cured Slab Samples

Based on the observations and discussion in the proceeding section of this chapter the following can be concluded, regarding site cured slab samples, and are considered as the key findings for this chapter:

- GGBS concrete in slabs exhibited definite sensitivity to curing at both 28 and 120 days for OPC and CEM I cements. At 28 days the oxygen permeability index for the various site-cured samples ranges from the "Poor" to "Good" durability category for OPC cement and spread between the "Good" and "Poor" durability categories for CEM I cement. The use of CEM I cement with GGBS results has had no effect at 28 days relative to OPC cement. At 120 days the oxygen permeability index results for the various site cured results to OPC cement are within the "Good" category, while they are within the "Poor" category for CEM I cement. In this case the use of CEM I has resulted in a reduction in the durability properties. At 28 days sand and hessian curing is more beneficial than the application of curing compound and no active curing for OPC and CEM I concretes. At 120 days the various site cured concrete exhibit effectively similar results and no active curing method emerges as more effective than another; and
- FA concrete in slabs exhibited definite sensitivity to curing at both 28 and 120 days for OPC and CEM I cements. At 28 days the oxygen permeability index for the various site-cured samples is within the "Good" durability category for OPC cement and spread between the "Good" and "Poor" durability categories for CEM I cement. The use of CEM I cement with FA results has had no effect at 28 days relative to OPC cement. At 120 days the oxygen permeability index results for the various site cured results to OPC cement are within the "Good" and "Excellent" category, while they are within the "Good" category for CEM I cement. In this case the use of CEM I has resulted in a marginal reduction in the durability properties. At 28

days sand curing is more beneficial than the application of curing compound for OPC and CEM I concretes. At 120 days the various site cured concrete exhibit effectively similar results and no active curing method emerges as more effective than another; and

- CSF concrete in slabs exhibited definite sensitivity to curing at both 28 and 120 days for OPC and CEM I cements. At 28 days the oxygen permeability index for the various site-cured samples is within the "Good" durability category for OPC cement and spread between the "Good" and "Poor" durability categories for CEM I cement. The use of CEM I cement with CSF results in a noticeable reduction in the durability properties at 28 days in relation to the OPC cement. At 120 days the oxygen permeability index results for the various site cured results to both OPC and CEM I cements are within the "Good" category. In this case the use of CEM I has had no effect on the durability properties. At 28 days sand curing is more beneficial than the application of curing compound or no active curing for OPC and CEM I concretes. At 120 days the various site cured concrete exhibit effectively similar results and no active curing method emerges as more effective than another.

7.4.3.6 General Summary Relating to Site Cured Samples (Walls and Slabs)

Table 91 represents a summary of all the data used in the this chapter and can be considered to be a summary of findings

TABLE 91: GENERAL SUMMARY OF OXYGEN PERMEABILITY INDEX RESULTS FOR ALL CONCRETE TYPES AND VARIOUS CURING REGIMES.

		OPC CEMENT				CEM I CEMENT	
		WALL SERIES		SLAB SERIES		SLAB SERIES	
		28 DAYS	120 DAYS	28 DAYS	120 DAYS	28 DAYS	120 DAYS
GGBS BINDER	CURING [A] SENSITIVITY	0,1 to 0,8	1,2 to 4,4	0,5 to 1,0	No data	0,3 to 1,3	0,2 to 0,8
GGBS BINDER	OXYGEN PERMEABILITY INDEX RESULTS	8,73 to 9,05 Uncured (9,05) Water (8,99) Formwork (8,93) Hessian (8,90) C. Comp. (8,73)	8,79 to 9,52 Water (9,52) Hessian (9,17) C. Comp. (9,04) Formwork (8,80) Uncured (8,79)	9,32 to 9,62 Water (9,62) Sand (9,76) Hessian (9,34) C. Comp. (9,45) Uncured (9,32)	9,48 to 9,89 Water (9,48) Sand (9,89) Uncured (9,87) C. Comp.(9,83) Hessian (9,80)	9,16 to 9,52 Water (9,52) Sand (9,42) Hessian (9,37) Uncured (9,26) C. Comp. (9,16)	9,49 to 9,69 Water (9,69) Hessian (9,60) Sand (9,59) Uncured (9,49) C. Comp. (9,44)
GGBS BINDER	CHANGE IN RESULTS WITH TIME [B]		45% increase to 245% reduction		30% increase to 260% reduction		47% to 91% reduction
FA BINDER	CURING [A] SENSITIVITY	3,5 to 7,5	0,7 to 7,9	1,0 to 1,5	0,3 to 0,8	0,5 to 2,8	0,3 to 0,5
FA BINDER	OXYGEN PERMEABILITY INDEX RESULTS	9,21 to 10,14 Water (10,14) Formwork (9,49) Hessian (9,26) Uncured (9,25) C. Comp. (9,21)	9,36 to 10,31 Water (10,31) Formwork(10,07) Uncured (9,64) Hessian (9,61) C. Comp. (9,36)	9,81 to 10,21 Water (10,21) Sand (9,90) C. Comp. (9,84) Uncured (9,84) Hessian (9,81)	9,91 to 10,11 Water (10,11) Uncured (10,00) Sand (9,91) Hessian (9,98) C. Comp. (9,85)	9,27 to 9,88 Sand (9,88) Uncured (9,86) Water (9,86) Hessian (9,68) C. Comp. (9,27)	9,79 to 9,95 Water (9,95) Uncured (9,85) Sand (9,82) C. Comp. (9,81) Hessian (9,79)
FA BINDER	CHANGE IN RESULTS WITH TIME [B]		40% to 280% reduction		20% increase to 47% reduction		13% increase to 240% reduction

TABLE 91: GENERAL SUMMARY OF OXYGEN PERMEABILITY INDEX RESULTS FOR ALL CONCRETE TYPES AND VARIOUS CURING REGIMES. (CONT.)

		OPC CEMENT				**CEM I CEMENT**	
		WALL SERIES		**SLAB SERIES**		**SLAB SERIES**	
		28 DAYS	**120 DAYS**	**28 DAYS**	**120 DAYS**	**28 DAYS**	**120 DAYS**
CSF BINDER	**CURING SENSITIVITY** [A]	0,3 to 1,4	1,5 to 2,1	0,2 to 0,3	0,7 to 1,0	0,4 to 2,4	0,2 to 0,9
	OXYGEN PERMEABILITY INDEX RESULTS	9,41 to 9,79 Water (9,79) Uncured (9,67) Hessian (9,60) Formwork (9,56) C. Comp. (9,41)	9,47 to 9,96 Water (9,96) Uncured (9,58) Hessian (9,55) Formwork (9,48) C. Comp. (9,47)	9,89 to 10,02 Water (10,02) Hessian (No data) Sand (9,92) C. Comp. (9,92) Uncured (9,89)	9,72 to 9,96 Water (9,96) Uncured (9,72) Hessian (9,67) C. Comp. (9,65) Sand (9,65)	9,26 to 9,78 Water (9,78) Sand (9,63) C. Comp. (9,42) Uncured (9,36) Hessian (9,26)	9,57 to 9,86 Water (9,86) Uncured (9,80) C. Comp. (9,66) Sand (9,61) Hessian (9,57)
	CHANGE IN RESULTS WITH TIME [B]		19% increase to 50% reduction		47% increase to 45% reduction		5% increase to 173% reduction

[A] Note: The curing sensitivity is indicated by the "curing reduction ratio".

[B] Note: The change in results with time is determined using the Darcy coefficient of permeability (k).

CHAPTER 8

GENERAL CONCLUSIONS AND THE WAY FORWARD

8.1 GENERAL CONCLUSIONS

8.1.1 ENVIRONMENTAL CHARACTERISATION SYSTEM

Central to this study was the development of an environmental characterisation system. Fortunately a recent laboratory study completed at the University of Cape Town[10] made it possible to formulate the basis of the system, however certain limitations were evident as follows:

- The laboratory based study was based on OPC as a binder while in this project three extenders were used, namely GGBS, FA and CSF;
- The mean temperature range measured on the test site varied from 10°C to 25°C, while the temperature model, based on the laboratory study, makes allowance for a temperature range from 18°C to 35°C;
- The mean relative humidity range measured on the test site varied from 20% to 100%, while the relative humidity model, based on the lab study, makes allowance for a relative humidity range from 40% to 80%; and
- The results on which the models are based are derived from a test condition having a period of wet curing of 1-day, a relative humidity of 50% and a temperature of 18°C. The interaction of these various environmental factors will certainly influence the data - in other words the model is not a true reflection of a single environmental factor. The ideal scenario would be to have information based on a lower relative humidity - 10% to 20%, a lower temperature - 5°C to 10°C, and an uncured sample, to enable the individual environmental factors to be measured in isolation.

Notwithstanding these limitations a sensitivity analysis was undertaken and an environmental characterisation system was developed for three regions in South Africa (Cape Town, Johannesburg and East London). The analysis showed sensitivity to the various regions and indicated that the system, although as yet unrefined, is a valuable tool. Of the three regional considered, East London was found to provide the most favourable environment for the development of durability index properties. Initially Durban was also considered, but was discarded from the analysis, due to the similarity of the climatic conditions to East London.

8.1.2 CHLORIDE CONDUCTIVITY

The chloride conductivity test measures the ionic conductivity of chloride ions through a concrete sample and is more related to the bulk properties of the concrete than the near surface properties. It has been shown by previous research[34] to be sensitive to concrete grade, and also binder types, particularly GGBS and FA. This is corroborated by this study where more favourable results were obtained from the FA and GGBS concretes relative to CSF concretes.

The chloride conductivity properties also responded to the change in cement type, with CEM I cement used with GGB resulting in poorer properties. The use of CEM I cement with FA and CSF yields concrete less sensitive to curing compared to OPC cement.

The effect of concrete grade is also evident in that the 30 MPa walls consistently produce poorer properties than the 35 MPa slabs.

The effect of curing is much less noticeable than the effect of binder type. Nevertheless the no active curing condition consistently produced the poorest properties at 120 days. Also the FA concrete is clearly more sensitive to curing, particularly when used with OPC cement.

The chloride conductivity improves substantially with time over the full 120 day test period, more so for FA concretes than GGBS and CSF concretes, and more so than the increase in compressive strength. This trend is an important finding, and runs somewhat contrary to previous laboratory work (e.g. by Griesel[54]) which indicates that even 3 days of wet curing is often able to produce properties not very different from those produced with 28 days of wet curing, which was assumed to be at or near the ultimate achievable value. However under benign site conditions, continued natural curing can have substantial benefits on the longer term properties, as evidenced by the 120-day results which were consistently and significantly better than the 28-day results.

What is unclear at this stage is how the durability properties continue to develop with time, beyond 120 days. Do they continue improving with age and at what rate, and more importantly, at what age does the improvement slow to become negligible?

This observation brings somewhat into question one of the underlying principles used in developing the environmental characterisation system in Chapter 4 of this study viz. the early age environmental weighting system (see page 47 of this document). In the absence of more data it is not possible, at this stage, to refine the characterisation system but it must be clearly stated that the assumption made in Chapter 4 will need to be reviewed.

Also noteworthy is that the durability properties for no curing improve with time for all three concretes, i.e. improvements in properties can result even in the absence of curing. This reinforces the findings of the analysis in Chapter 4, that the climate in East London is favourable to the development of durability indexes.

The benign environment of East London has masked the sensitivity of the site curing methods. In other words the observation relating to the improvement of the no cured condition with time will in all probability not be repeated in other regions with a harsher climate. It is thus important to view the site curing efficiency in relation to the environmental rating developed for a particular area or region. Unfortunately in the case of this study the masking effect is so pronounced that it is not possible to comment on the effectiveness of the various site curing methods. It must be stressed that this does not suggest that curing has no benefit, but rather that the environment and curing interact in developing durability properties.

8.1.3 WATER SORPTIVITY

The water sorptivity test measures the rate of absorption of water into a concrete sample and has been shown by previous researchers[33] to be sensitive to degree of initial curing. The test is more related to the near-surface properties of the concrete and not the bulk material properties. This test is best done on young concretes as older concretes may be contaminated with salts, or be carbonated which alters the absorption of the water into the pore structure.

The benefits of curing are borne out by the fact that full water curing consistently produces the best results regardless of concrete type or element. Also of interest is that the variation between the fully water cured results is relatively small between the various concretes and test elements. It is also noted that all the concretes, regardless of cement type have similar sensitivities to curing (exhibited by the curing reduction ratio).

The same trend, as for chloride conductivity, regarding the improvement of properties with time is evident. In this case, however, the degree of improvement is similar for all three concretes; both test elements and cement types. Once again the same questions apply, and also the comments regarding the environment.

8.1.4 OXYGEN PERMEABILITY INDEX

The oxygen permeability index is based on the Darcy coefficient determined by the flow of oxygen through a concrete sample and has been shown by previous researchers[33] to be sensitive to concrete grade, binder type and curing. The test is more related to the microstructure of the concrete or rather the size and distribution of pores in the concrete sample that can facilitate gas flow. In the case of this index the hydration of the binder in the concrete in creating a dense microstructure plays a major role. CSF when used in concrete has the tendency to reduce the permeability considerably[35] due to the highly pozzolanic nature of the material and extreme fineness and the material is often referred to as a "fine filler". FA although not as fine as CSF also has a highly pozzolanic nature and is noted as reducing permeability by acting as a filler material[36]. It is noted however that for both of these materials the pozzolanic reaction can only proceed in the presence of available moisture, thus curing is important.

When considering the test data it is noted that the FA and CSF concretes produce more favourable properties than the GGBS concretes, as may be expected from the above discussion. The results also clearly bear out the high sensitivity of FA concrete to curing. Also of note is the poor performance of CEM I cement relative to OPC cement with noticeably poorer properties developed particularly for CSF and GGBS. This highlights the importance of the compatibility of the cement and extender in producing a dense pore structure.

The curing sensitivity is markedly more noticeable for walls than slabs for all of the concretes, and particularly for FA concrete. Not only are the walls a lower grade of concrete than the slabs, but also the effectiveness of curing for the walls is less than for slabs given the orientation of the curing face.

Once again the trend regarding the improvement of properties with time is clearly evident. In this case, however, the improvement is very variable and follows no set pattern. The same questions as noted previously apply, as also the comments regarding the environment.

8.2 THE WAY FORWARD

a) The environmental characterisation system requires refinements in that a study similar to the one undertaken by Griesel[54] is required with the following refinements:

- FA, GGBS and CSF concretes must be added;
- The limits of temperature and relative humidity must be expanded to accommodate the full climatic range experienced in South Africa, and also in order to make it possible to distinguish between the effects of temperature and relative humidity;
- The durability indexes must be determined at a series of element ages to facilitate evaluation of development of properties with time.

b) With the above information it will be possible to refine the system and then to correlate it with real site based results for various climatic regions in South Africa. Only then will it be possible to gain a fuller understanding of the complex interaction between curing, the environment and various binder interactions.

c) The interaction between cement type and extender requires more investigation. While this study used cement from one source only, a study evaluating the effect of various cements from various sources will indicate the compatibility of extender and cement type in developing acceptable durability properties.

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APPENDIX 1

1:10 000 LOCALITY PLAN : PORT OF EAST LONDON


TEST SITE
No 2
TEST SITE
No 1
LOCALITY PLAN
PORT OF EAST LONDON
SCALE 1 : 10 000

APPENDIX 2

PHOTOGRAPHIC SURVEY

PHOTOGRAPH 1

This photograph is taken looking North and shows test site No. 1 (the slabs). Note the precast concrete wall on the northern boundary, also the aggregates (stored under tarpaulin) against the wall. The portable concrete mixer visible on the eastern face of the photograph was used to batch the concrete. Note how each slab panel is split into four segments (one per site curing method).

PHOTOGRAPH 2

This photograph is taken looking East towards the southern break wall of the East London Port (visible in the background). The Buffalo River mouth is clearly visible in the foreground.

PHOTOGRAPH 3

This photograph is taken from the same position as photograph 1, showing the complete set of slab test elements (12 in total 2 elements are partly covered by shotblast debris in the foreground). The slab 1 series are closest to the camera with the slab 4 series furthest from the camera.

PHOTOGRAPH 4

This photograph is taken looking North and shows test site No. 2 (the walls). The Buffalo River is clearly visible in the background. Note the four separate panels per wall series (one per site curing method).

PHOTOGRAPH 5

This photograph is taken from the same position as photograph 4 but looking North-East. The East bank of the Port of East London is visible in the background.

PHOTOGRAPH 6

This photograph is taken on the East bank of the port looking towards the mouth of the Buffalo River shows the mass concrete paving under construction. The initial planning was to use designated sites on this element as a test area. It was later decided however to cast stand-alone test slabs (as seen in photograph 1).

PHOTOGRAPH 7

This photograph s taken on the West bank of the Port looking away from the Buffalo River shows the reinforced concrete retaining wall constructed to facilitate the placing of a Civil Engineer Maintenance Depot for the Port. As with the concrete paving the initial intention was to use parts of the element as a test area. It was later decided however to cast stand-alone test walls (as seen in photographs 4 and 5).

PHOTOGRAPH 8

This photograph shows the steel formwork fabricated to facilitate the casting of the test slabs (test site 1).

PHOTOGRAPH 9

This photograph shows the equipment used to batch the various test mixes. Note the mass balance in the centre of the photograph used to ensure the correct proportions of the dry constituents.

PHOTOGRAPH 10

This photograph shows the control of water added to the mix by using a slump cone. Note the mix rehology as indicated by a "true" slump.

PHOTOGRAPH 11

This photograph shows the placing and compaction of one of the slab series test elements. Note the poker vibrator used for compaction and also the portable concrete mixer visible on the left hand side of the photograph.

PHOTOGRAPH 12

This photograph shows the striking-off of the concrete surface to the slab test elements. Note the slab split into four using a nosing tool, the brush finish and the identification tags. In the background the curing of two slab elements is visible.

PHOTOGRAPH 13

This photograph shows the application of the site curing methods. Note how the hessian is applied in a double layer, well saturated and then covered with a green plastic sheet (see photograph 15). Note the thickness of the sand layer (± 75mm) and also the resin based pigmented curing compound (see photograph 14 for application).

PHOTOGRAPH 14

This photograph shows the application of a pigmented resin-based curing compound to a slab test element. Portable spray equipment was used as indicated.

PHOTOGRAPH 15

This photograph shows the green plastic sheet covering to the hessian (note how the edges are secured). Also note the sand layer well saturated after placing.

PHOTOGRAPH 16

This photograph shows the wall test elements under the site-curing action as follows from left to right.

- No curing
- The application of a pigmented resin-based curing compound.
- Hessian curing covered with a green plastic sheet.
- The retention of formwork (Note in this case timber forms were used).

PHOTOGRAPH 17

This photograph shows the extraction of core samples at 28 days to a wall test element (the coring equipment is visible and discussed under photograph 19). Note that a total of 8 cores per element were extracted (4 off ~ 150mm length and 4 off ~ 80mm length). At 120 days only 6 cores were extracted (3 off ~ 150mm length and 3 off ~ 80mm length). The cores were removed using a small cold steel chisel and a 4 lb. hammer (visible in the photograph).

PHOTOGRAPH 18

This photograph shows a set of cores extracted per seasonal cast series at 28 days. As per the walls, 8 cores were extracted at 28 days and 6 cores at 120 days. Note the east bank breakwall in the background.

PHOTOGRAPH 19

This photograph shows the coring equipment and drive unit used as supplied by a local materials laboratory. The core motor was hydraulically driven with the hydraulic pump powered by a petrol-fuelled rotary motor. The core motor housing is held in place by a large baseplate (visible under the operators feet) fixed by a steel pipe and guide arm. In the case of both test sites it was possible to connect watermain pressure for the lubrication (as visible in the foreground). Note the maize export storage facility in the background on the west bank of the Port.

PHOTOGRAPH 20

This photograph shows the temperature-controlled curing bath where the reference samples were cured. Note the thermostat, the circulation pump and the floating thermometer.

APPENDIX 3

EXAMPLE WORKSHEET SHOWING FORMAT OF CUBE STRENGTH DATA

EXAMPLE WORKSHEET SHOWING FORMAT OF CUBE STRENGTH DATA

Mark	Cast Date	Test Date	Age (days)	Mass (g)	Density (kg/m^3)	fcu (Mpa)	SD	Tu (upper)	Tl (lower)	5% SL	10% SL
Wall A	30-Apr-97	08-May-97	8	8531	2527.7	24.2		0.732			
Wall A	30-Apr-97	08-May-97	8	8468	2509.0	21.9			1.129		
Wall A	30-Apr-97	08-May-97	8	8509	2521.2	23.8					
Average						23.3	1.229			1.153	1.148
Wall A	30-Apr-97	15-May-97	15	8506	2520.3	33.4		1.145			
Wall A	30-Apr-97	15-May-97	15	8569	2539.0	30.9					
Wall A	30-Apr-97	15-May-97	15	8570	2539.3	30.5			0.700		
Average						31.6	1.572			1.153	1.148
Wall A	30-Apr-97	28-May-97	28	8553	2535.4	35.5					
Wall A	30-Apr-97	28-May-97	28	8427	2496.9	37.1					
Average						36.3	1.131			n/a	n/a
Wall A	30-Apr-97	03-Jul-97	64	8534	2528.6	44.2					
Wall A	30-Apr-97	03-Jul-97	64	8511	2521.8	44.3					
Average						44.3	0.071			n/a	n/a

Age	fcu
0	0
8	23.3
15	31.6
28	36.3
61	44.3

APPENDIX 4

EXAMPLE WORKSHEET SHOWING FORMAT OF CORE STRENGTH DATA

EXAMPLE WORKSHEET SHOWING FORMAT OF CORE STRENGTH DATA

Cast	30-Apr-97
Cored	29-May-97
Age (days)	29
Tested	09-Jun-97

Core Mark	Mass (grams)	Density (kg/m^3)	Diameter (mm)	Length (mm)	Failure Load (kN)	fcu (Mpa)	SD	Tu (upper)	Tl (lower)	5% SL
WA:Cube(1)	[illegible]	2445.3	67.2	68.2	127.0	35.3	-	-	-	-
Average						35.3	n/a	n/a	n/a	n/a
WA:C(e)	621.8	2514.6	67.6	69.0	128.0	35.7				
WA:C(f)	624.0	2650.4	67.7	65.5	128.5	35.8				
WA:C(g)	620.2	2508.1	67.6	69.0	125.5	35.0			1.586	
WA:C(h)	626.7	2529.3	66.8	70.7	125.5	35.1		0.907		
Average						35.6	0.451			1.463
WA:F(e)	645.8	2513.8	67.7	71.2	115.0	31.9				
WA:F(f)	587.8	2496.7	67.7	65.5	109.5	30.5			0.977	
WA:F(g)	647.6	2541.2	67.7	70.9	119.5	33.2				
WA:F(h)	610.2	2503.9	67.6	68.0	137.0	36.8		1.363		
Average						33.1	2.722			1.463
WA:H(e)	645.7	2497.9	67.8	71.6	[illegible]	36.8		1.169		
WA:H(f)	640.9	2499.4	67.6	71.6	129.0	36.0				
WA:H(g)	623.2	2469.2	68.0	69.6	132.0	36.4				
WA:H(h)	629.8	2472.7	67.3	71.6	126.5	35.6			[illegible]	
Average						36.2	0.547			1.463
WA:N(e)	618.8	2451.4	67.4	70.8	124.0	34.8				
WA:N(f)	624.5	2482.2	67.6	70.1	122.5	34.1			1.124	
WA:N(g)	623.2	2469.2	68.0	69.6	132.0	36.4		0.962		
WA:N(h)	623.5	2674.9	65.3	69.6	121.0	36.1				
Average						35.4	1.068			1.463

Mark	fcu
WA:H	36.2
WA:C	35.6
WA:N	35.4
WA:Cube	35.3
WA:F	33.1

APPENDIX 5

EXAMPLE WORKSHEET SHOWING FORMAT OF CHLORIDE CONDUCTIVITY DATA

EXAMPLE WORKSHEET SHOWING FORMAT OF CHLORIDE CONDUCTIVITY DATA

Cast	30-Apr-97
Cored	29-May-97
Test	10-Jun-97
Age	29 days

Sample Mark	Thickness (mm)	Diameter (mm)	Current (mA)	Voltage (V)	Conduct. (mS/cm)	Average (mS/cm)	SD	Ta (upper)	Tl (lower)	5% SL
WA: F(e)	26.4	67.70	77.00	10.12	0.56					
WA: F(f)	27.1	67.65	75.00	10.02	0.56			0.912		
WA: F(g)	25.4	67.65	69.00	10.08	0.48					
WA: F(h)	25.6	67.55	70.00	10.46	0.48				0.925	
						0.52	0.05			1.463
WA: H(e)	24.3	67.80	91.00	10.14	0.60			1.09		
WA: H(f)	27.1	67.55	76.00	10.08	0.57					
WA: H(g)	27.4	67.95	78.00	10.17	0.58					
WA: H(h)	26.2	67.30	[illegible]	10.08	0.53				1.221	
						0.57	0.03			1.463
WA: C(e)	27.4	67.55	120.00	10.20	0.90					
WA: C(f)	27.8	67.65	116.00	10.32	0.87					
WA: C(g)	26.2	67.55	118.00	10.51	0.82				1.299	
WA: C(h)	26.6	66.90	133.00	10.11	0.92			1.021		
						0.88	0.04			1.463
WA: N(e)	26.4	67.40	96.00	10.05	0.66			1.0[illegible]		
WA: N(f)	26.3	67.60	76.00	10.08	0.55				0.936	
WA: N(g)	24.9	67.95	83.00	10.15	0.56					
WA: N(h)	26.8	65.30	84.00	10.40	0.65					
						0.61	0.06			1.463
WA-Cube(1)	23.0	67.65	75.00	10.40	0.46			1.084		
WA-Cube(2)	25.0	67.65	45.00	10.20	0.31					
WA-Cube(3)	29.5	67.65	28.60	10.50	0.22				0.887	
						0.33	0.12			1.153

Sample Mark	Average (mS/cm)
WA:Cube	0.33
WA: F	0.52
WA: H	0.57
WA: N	0.61
WA: C	0.88

APPENDIX 6

EXAMPLE WORKSHEETS SHOWING FORMAT OF WATER SORPTIVITY DATA

EXAMPLE WORKSHEET SHOWING FORMAT OF WATER SORPTIVITY DATA

Mark	Sorptivity	Average Sorptivity	Standard Deviation	Tu (upper)	Tl (lower)	5% SL	10% SL
WA:Cube(1)	7.68				0.984		
WA:Cube(2)	7.93						
WA:Cube(3)	9.49			1.133			
WA:Cube(4)	8.97						
		8.52	0.854			1.463	1.425
WA:C(a)	11.36			1.381			
WA:C(b)	10.53						
WA:C(c)	10.31				0.944		
WA:C(d)	10.74						
		10.73	0.453			1.463	1.425
WA:F(a)	12.58			0.914			
WA:F(b)	11.91				1.327		
WA:F(c)	12.49						
WA:F(d)	12.25						
		12.31	0.299			1.463	1.425
WA:H(a)	[illegible]						
WA:H(b)	8.16				1.167		
WA:H(c)	12.53						
WA:H(d)	13.85			1.367			
		11.14	2.547			1.463	1.425
WA:N(a)	11.53						
WA:N(b)	16.02			1.165			
WA:N(c)	13.35						
WA:N(d)	8.56				1.214		
		12.36	3.135			1.463	1.425

Mark	Average Sorptivity
Cube:WA	8.52
WA:C	10.73
WA:H	11.14
WA:F	12.31
WA:N	12.36

EXAMPLE OF WORKSHEET SHOWING FORMAT OF WATER SORPTIVITY DATA

Sample	WA:N(a)
Cast	30-Apr-97
Cored	29-May-97
Age (days)	29

Time (min)	Time (hr)	Sqrt Time	Mass Change	Mass Gain (g)
0.00	0.00	0.00	221.60	0.00
1.00	0.02	0.13	222.80	1.20
6.00	0.10	0.32	223.90	2.30
12.00	0.20	0.45	224.60	3.00
20.00	0.33	0.58	225.20	3.60
32.00	0.53	0.73	225.90	4.30

Thickness	26.50
Sat. Mass	234.80
Diametre	67.50
Slope	5.74479
Correlation	0.98381
Sorptivity	11.53

Sample	WA:N(b)
Cast	30-Apr-97
Cored	29-May-97
Age (days)	29

Time (min)	Time (hr)	Sqrt Time	Mass Change	Mass Gain (g)
0.00	0.00	0.00	233.50	0.00
1.00	0.02	0.13	235.10	1.60
6.00	0.10	0.32	236.30	2.80
12.00	0.20	0.45	237.20	3.70
20.00	0.33	0.58	237.80	4.30
32.00	0.53	0.73	238.30	4.80

Thickness	29.80
Sat. Mass	245.50
Diametre	67.50
Slope	6.44974
Correlation	0.95932
Sorptivity	16.02

Sample	WA:N(c)
Cast	30-Apr-97
Cored	29-May-97
Age (days)	29

Time (min)	Time (hr)	Sqrt Time	Mass Change	Mass Gain (g)
0.00	0.00	0.00	238.40	0.00
1.00	0.02	0.13	239.80	1.40
6.00	0.10	0.32	240.90	2.50
12.00	0.20	0.45	241.70	3.30
20.00	0.33	0.58	242.30	3.90
32.00	0.53	0.73	242.80	4.40

Thickness	27.50
Sat. Mass	250.60
Diametre	67.50
Slope	5.92036
Correlation	0.96755
Sorptivity	13.35

Sample	WA:N(d)
Cast	30-Apr-97
Cored	29-May-97
Age (days)	29

Time (min)	Time (hr)	Sqrt Time	Mass Change	Mass Gain (g)
0.00	0.00	0.00	257.20	0.00
1.00	0.02	0.13	258.60	1.40
6.00	0.10	0.32	259.50	2.30
12.00	0.20	0.45	260.00	2.80
20.00	0.33	0.58	260.40	3.20
32.00	0.53	0.73	260.80	3.60

Thickness	29.80
Sat. Mass	269.90
Diametre	67.50
Slope	3.64654
Correlation	0.98184
Sorptivity	8.56

APPENDIX 7

EXAMPLE WORKSHEETS SHOWING FORMAT OF OXYGEN PERMEABILITY INDEX DATA

Mark	Oxygen Permeability	Average O2 Perm.	Standard Deviation	Tu (upper)	Tl (lower)	5% SL	10% SL
WA:Cube(1)	8.55						
WA:Cube(2)	8.27				1.030		
WA:Cube(3)	9.75			1.302			
WA:Cube(4)	9.38						
		8.99	0.691			1.463	1.425
WA:C(a)	8.67						
WA:C(b)	8.89			1.400			
WA:C(c)	8.63				0.883		
WA:C(d)	8.73						
		8.73	0.113			1.463	1.425
WA:F(a)	8.72			–	–		
WA:F(b)	8.94			0.871			
WA:F(c)	8.93						
WA:F(d)	8.91				1.092		
		8.93	0.019			1.153	1.148
WA:H(a)	8.83				1.449		
WA:H(b)	8.92						
WA:H(c)	8.87						
WA:H(d)	8.96			1.099			
		8.90	0.055			1.463	1.425
WA:N(a)	9.04						
WA:N(b)	9.13						
WA:N(c)	9.20			0.958			
WA:N(d)	8.84				1.356		
		9.05	0.155			1.463	1.425

Discard result

Mark	Average O2 Perm.
WA:N	9.05
Cube:WA	8.99
WA:F	8.93
WA:H	8.90
WA:C	8.73

EXAMPLE WORKSHEETS SHOWING FORMAT OF OXYGEN PERMEABILITY INDEX DATA

Cast	30-Apr-97		
Cured	29-May-97		
Age (days)	29		
Starting pressure	6.984		
Initial pressure	0.525		
Gradient	15.48		
Constant	-8.13		
Sample	WA:N(a)		
Time (secs)	Raw Data	Pressure (kPa)	Ln(Po/P)
0	6.984	100.00	0.000
1000	5.595	78.50	0.242
2000	4.591	62.95	0.463
3000	3.824	51.08	0.672
4000	3.219	41.71	0.874
5000	2.740	34.29	1.070
6000	2.364	28.47	1.256
7000	2.054	23.67	1.441
8000	1.790	19.59	1.630
9000	1.575	16.26	1.817
10000	1.394	13.45	2.006
11000	1.253	11.27	2.183
12000	[illegible]	9.38	2.356
Slope	[illegible]		
Correlation Coefficient	0.9986013		
Thickness	26.5		
w (kg/mol)	32		
V (m^3)	0.00495		
g (m/s^2)	9.81		
d (m)	0.0265		
R (Nm/Kmol)	8313		
diameter (m)	0.0675		
A (m^2)	0.00357847		
Kelvin	293		
z (slope)	0.000194459		
COEFF k	9.13792E-10		
OPI	9.04		

Cast	30-Apr-97		
Cured	29-May-97		
Age (days)	29		
Starting pressure	8.591		
Initial pressure	0.854		
Gradient	11.71		
Constant	-0.63		
Sample nr	WA:N(b)		
Time (secs)	Raw Data	Pressure (kPa)	Ln(Po/P)
0	8.591	100.00	0.000
1000	7.316	85.07	0.162
2000	6.271	72.82	0.317
3000	5.409	62.73	0.466
4000	4.672	54.09	0.614
5000	4.056	46.88	0.758
6000	3.541	40.85	0.895
7000	3.101	35.69	1.030
8000	2.703	31.63	1.170
9000	2.369	27.12	1.305
10000	2.078	23.71	1.439
11000	1.827	20.77	1.572
12000	1.607	18.19	1.704
Slope	[illegible]		
Correlation Coefficient	0.9991442		
Thickness	29.8		
w (kg/mol)	32		
V (m^3)	0.00495		
g (m/s^2)	9.81		
d (m)	0.0298		
R (Nm/Kmol)	8313		
diameter (m)	0.0675		
A (m^2)	0.00357847		
Kelvin	297		
z (slope)	0.000141512		
COEFF k	7.49159E-10		
OPI	9.13		

EXAMPLE WORKSHEETS SHOWING FORMAT OF OXYGEN PERMEABILITY INDEX DATA

Cast	30-Apr-97
Cored	29-May-97
Age (days)	29
Starting pressure	7.624
Initial pressure	0.432
Gradient	13.90
Constant	-6.01
Sample nr:	WA:N(c)

Time (secs)	Raw Data	Pressure (kPa)	Ln(Po/P)
0	7.624	100.00	0.000
1000	6.684	86.93	0.140
2000	5.888	75.86	0.276
3000	5.206	66.38	0.410
4000	4.608	58.06	0.544
5000	4.100	51.00	0.673
6000	3.665	44.95	0.800
7000	3.284	39.66	0.925
8000	2.938	34.84	1.054
9000	2.640	30.70	1.181
10000	2.376	27.03	1.308
11000	2.151	23.90	1.431
12000	1.949	21.09	1.556

Slope	1.292E-04
Correlation Coefficient	0.9997326
Thickness	27.5
w (kg/mol)	32
V (m^3)	0.00195
g (m/s^2)	9.81
d (m)	0.0275
R (Nm/Kmol)	8313
diameter (m)	0.0675
A (m^2)	0.00357847
Kelvin	293
z (slope)	0.000129161
COEFF k	6.33238E-10
O.P.I.	9.20

Cast	30-Apr-97
Cored	29-May-97
Age (days)	29
Starting pressure	8.706
Initial pressure	0.380
Gradient	11.49
Constant	0.00
Sample nr:	WA:N(d)

Time (secs)	Raw Data	Pressure (kPa)	Ln(Po/P)
0	8.706	100.00	0.000
1000	6.364	73.10	0.313
2000	4.733	54.36	0.609
3000	3.563	40.93	0.893
4000	2.694	30.94	1.173
5000	2.056	23.62	1.443
6000	1.585	18.21	1.703
7000	1.228	14.11	1.959
8000	0.933	10.72	2.233
9000	0.718	8.25	2.495
10000	0.547	6.28	2.767
11000	0.420	4.82	3.032
12000	0.322	3.70	3.297

Slope	2.717E-04
Correlation Coefficien	0.9995090
Thickness	29.8
w (kg/mol)	32
V (m^3)	0.00495
g (m/s^2)	9.81
d (m)	0.0298
R (Nm/Kmol)	8313
diametre (m)	0.0675
A (m^2)	0.00357847
Kelvin	293
Z (slope)	0.000271669
COEFF k	1.44341E-09
O.P.I.	8.84

APPENDIX 8

EXTRACTS FROM THE AMERICAN NATIONAL STANDARDS PUBLICATION: "STANDARD PRACTICE FOR DEALING WITH OUTLYING OBSERVATIONS"

4. Recommended Criteria for Single Samples

4.1 Let the sample of n observations be denoted in order of increasing magnitude by $x_1 \leq x_2 \leq x_3 \leq \ldots \leq x_m$ Let x_n be the doubtful value, that is the largest value. The test criterion, T_n recommended here for a single outlier is as follows :

$$T_n = (x_n - \bar{x})/s$$

where :

$\bar{x}$ = arithmetic average of all n values and

s = estimate of the population standard deviation based on the sample data, calculated as follows :

If x, rather than x_n is the doubtful value, the criterion is as follows :

$$T_1 = (\bar{x} - x_1)/s$$

The critical values for either case, for the 1 and 5 % levels of significance, are given in Table 1. Table 1 and the following tables give the "one-sided" significance levels. In the previous tentative recommended practice (1961), the tables listed values of significance levels double those in the present practice since it was considered that the experimenter would test either the lowest or the highest observation (or both) for statistical significance. However, to be consistent with actual practice and in an attempt to avoid further misunderstanding single-sided significance levels are tabulated here so that both viewpoints can be represented.

4.2 The hypothesis that we are testing in every case is that all observations in the sample come from the same normal population. Let us adopt, for example, a significance level of 0.05. If we are interested *only* in outliers that occur on the *high side*, we should always use the statistic $T_n = (x_n - \bar{x})/s$ and take as critical value the 0.05 point of Table 1. On the other hand, if we are interested *only* in outliers occurring on the *low side*, we would always use the statistic $T_1 = (\bar{x} - x_1)/s$ and again take as a critical value the 0.05 point of Table 1. Suppose, however, that we are interested in outliers occurring on *either side*, but do not believe that outliers can occur on both sides simultaneously. We might, for example, believe that at some time during the experiment something possibly happened to cause an extraneous variation on the high side or on the low side but that it was very unlikely that two or more such events should have occurred, one being an extraneous variation on the high side *and* the other an extraneous variation on the low side. With this point of view we should use the statistic $T_n = (x_n - \bar{x})/s$ of the statistic $T_1 = (\bar{x} - x_1)/s$ whichever is larger. If in this instance we use the 0.05 point of Table 1 as our critical value, the true significance level would be twice 0.05 or 0.10. If we wish a significance level of 0.05 and not 0.10, we must in this case use as a critical value the 0.025 point of Table 1. Similar considerations apply to the other tests given below.

4.2.1 *Example 1* – as an illustration of the use of T_n and Table 1, consider the following ten observations on breaking strength (in pounds) of 0.104-in. hard-drawn copper wire: 568, 570, 570, 570, 572, 572, 572, 578, 584, 596. The doubtful observation is the high value, $x_{10} = 596$. Is the value of 596 significantly high? The mean is $\bar{x} = 575.2$ and the estimated standard deviation is $s = 8.70$. We compute

$$T_{10} = (596 - 575.2)/8.70 = 2.39$$

From Table 1, for $n = 10$, note that a T_{10} as large as 2.39 would occur by chance with probability less than 0.05. In fact, so large a value would occur by chance not much more often than 1% of the time. Thus the weight of the evidence is against the doubtful value having come from the same population as the others (assuming the population is normally distributed). Investigation of the doubtful value is therefore indicated.

TABLE 1: CRITICAL VALUES FOR T (ONE-SIDED TEST) WHEN STANDARD DEVIATION IS CALCULATED FROM THE SAME SAMPLE

NUMBER OF OBSERVATIONS *N*	UPPER 0.1% SIGNIFICANCE LEVEL	UPPER 0.5% SIGNIFICANCE LEVEL	UPPER 1% SIGNIFICANCE LEVEL	UPPER 2.5% SIGNIFICANCE LEVEL	UPPER 5% SIGNIFICANCE LEVEL	UPPER 10% SIGNIFICANCE LEVEL
3	1.155	1.155	1.155	1.155	1.153	1.148
4	1.499	1.496	1.492	1.481	1.463	1.425
5	1.780	1.764	1.749	1.715	1.672	1.602
6	2.011	1.973	1.944	1.887	1.822	1.729
7	2.201	2.139	2.097	2.020	1.938	1.828
8	2.358	2.274	2.221	2.126	2.032	1.909
9	2.492	2.387	2.323	2.215	2.110	1.977
10	2.606	2.482	2.410	2.290	2.176	2.036

APPENDIX 9

ENVIRONMENTAL CHARACTERISATION SYTEM: WORKED EXAMPLE

This appendix details the calculation of the 28-day, overall environmental rating of a site cured element (in this case wall A) based on the response to Chloride Conductivity. The table below indicates the raw climatic data recorded relative to element age and then calculates the site (element) scoring as also the control (wet cured cube) scoring. The element ages are conveniently grouped to facilitate the application of the hydration rate weighting.

RAW ENVIRONEMENTAL DATA AND SCORING TO WALL A, FOR DETERMINATION OF ENVIRONMENTAL RATING TO CHLORIDE CONDUCTIVITY INDEX

	RELATIVE HUMIDITY			TEMPERATURE			PRECIPITATION			
		SCORING			SCORING				SCORING	
Age (days)	**Mean Daily R.H. (%)**	**Site**	**Control**	**Mean Daily Temp (° C)**	**Site**	**Control**	**Vol. (mm)**	**Duration (min)**	**Site**	**Control**
1	89	10.0	10.0	15.5	10.0	8.0			0.0	10
2	81	10.0	10.0	15.3	10.0	8.0	0.4	5	0.1	10
3	78	9.7	10.0	16.7	10.0	8.0			0.0	10
		29.7	**30.0**		**30.0**	**24.0**			**0.1**	**30**
4	86	10.0	10.0	15.6	10.0	8.0	1.6	10	0.3	10
5	74	9.2	10.0	16.8	10.0	8.0			0.0	10
6	78	9.7	10.0	17.2	10.0	8.0	0.5	5	0.1	10
7	72	8.9	10.0	17.5	10.0	8.0			0.0	10
		37.9	**40.0**		**40.0**	**32.0**			**0.4**	**40**
8	78	9.7	10.0	18.1	10.0	8.0	5.6	29	1.0	10
9	95	10.0	10.0	16.2	10.0	8.0	45.9	210	6.0	10
10	83	10.0	10.0	17.9	10.0	8.0	7.4	40	1.4	10
11	86	10.0	10.0	17.1	10.0	8.0			0.0	10
12	83	10.0	10.0	17.4	10.0	8.0			0.0	10
13	83	10.0	10.0	16.7	10.0	8.0			0.0	10
14	80	10.0	10.0	17.5	10.0	8.0			0.0	10
		69.7	**70.0**		**70.0**	**56.0**			**8.4**	**70**
15	76	9.5	10.0	16.4	10.0	8.0			0.0	10
16	73	9.1	10.0	16.5	10.0	8.0	0.2	5	0.1	10
17	73	9.1	10.0	16.5	10.0	8.0			0.0	10
18	59	6.1	10.0	18.4	9.8	8.0			0.0	10
19	27	0.0	10.0	23.1	8.0	8.0			0.0	10
20	26	0.0	10.0	25.0	7.2	8.0			0.0	10
21	64	7.7	10.0	17.1	10.0	8.0			0.0	10
22	67	8.3	10.0	15.4	10.0	8.0			0.0	10
23	79	9.9	10.0	16.7	10.0	8.0			0.0	10
24	61	6.7	10.0	20.0	9.2	8.0			0.0	10
25	59	6.1	10.0	20.4	9.0	8.0			0.0	10
26	92	10.0	10.0	17.7	10.0	8.0	11.8	55	2.1	10
27	87	10.0	10.0	16.8	10.0	8.0	0.4	10	0.2	10
28	69	8.5	10.0	12.8	10.0	8.0	23.6	120	4.0	10
29	72	8.9	10.0	9.9	10.0	8.0	13.2	115	2.9	10
30	74	9.2	10.0	12.3	10.0	8.0	0.4	10	0.2	10
		119.0	**160.0**		**153.2**	**128.0**			**9.5**	**160.0**

The scoring generated in the table above is used in each of the tables below to determine the weighted score for both the site (element) and control (wet cured cube) for each of the three climatic influences. A hydration rate weighting is applied to a grouped scoring and accumulated to yield a weighted scoring for both the site and control scenarios. The site scenario is then represented as a ratio relative to the control weighted scoring, per climatic influence. Each of the three tables below details the calculation of the weighted scoring for Relative Humidity, Temperature and Precipitation.

SUMMARY OF WEIGHTED RELATIVE HUMIDITY SCORING

Age (days)	SCORING		Hydration Rate Weighting (%)	WEIGHTED SCORING	
	Control	Site		Control	Site
1-3	30.0	29.7	30%	9.0	8.9
4-7	40.0	37.9	20%	8.0	7.6
8-14	70.0	69.7	15%	10.5	10.5
15-30	160.0	119.0	15%	24.0	17.8
				51.5	**44.8**
				87.0%	

The weighted Relative Humidity scoring to wall A for 28 days, based on the response to Chloride Conductivity, indicates that the site Relative Humidity could be expected to impart a potential Chloride Conductivity of 87,0% of that of full water curing for the same period (control).

SUMMARY OF WEIGHTED TEMPERATURE SCORING

Age (days)	SCORING		Hydration Rate Weighting (%)	WEIGHTED SCORING	
	Control	Site		Weighted Cube	Weighted Element
1-3	24.0	30.0	30%	7.2	9.0
4-7	32.0	40.0	20%	6.4	8.0
8-14	56.0	70.0	15%	8.4	10.5
15-30	128.0	153.2	15%	19.2	23.0
				41.2	**50.5**
				122.5%	

As above the weighted temperature scoring to wall A for 28 days, based on the response to Chloride Conductivity, indicates that the site temperature could be expected to impart a potential Chloride Conductivity of 122,5% of that of full water curing for the same period (control). In other words the site temperature conditions were more favourable to the development of potential chloride conductivity properties than the control condition.

SUMMARY OF WEIGHTED PRECIPITATION SCORING

Age (days)	SCORING		Hydration Rate Weighting (%)	WEIGHTED SCORING	
	Control	Site		Weighted Cube	Weighted Element
1-3	30.0	0.1	30%	9.0	0.0
4-7	40.0	0.4	20%	8.0	0.1
8-14	70.0	8.4	15%	10.5	1.3
15-30	160.0	9.5	15%	24.0	1.4
				51.5	**2.8**
				5.4%	

The same argument as above applies to the precipitation scoring.

To represent the influence and relative effect of each of the three climatic influences as a single index or rating a further overall weighting system is applied to the three individual weighted scores as determined above. In other words the influences of temperature, relative humidity and precipitation, on developing potential chloride conductivity, is not taken as equal as explained in more detail in chapter 4.

FINAL OVERALL ENVIRONMENTAL RATING FOR WALL SERIES AT 28 DAYS, BASED ON RESPONSE TO CHLORIDE CONDUCTIVITY

	TEMPERATURE	WF	RELATIVE HUMIDITY	WF	PRECIPITATION	WF	FINAL RATING
WALL A	122.5%	20.0%	87.0%	20.0%	5.4%	60.0%	**45.2%**
WALL B	122.2%	20.0%	79.8%	20.0%	0.6%	60.0%	**40.7%**
WALL C	123.8%	20.0%	84.6%	20.0%	5.4%	60.0%	**44.9%**

The final rating is thus an indication of the ratio of potential chloride conductivity that can be expected to develop on site relative to the control for the given environmental exposure conditions. Not only is this rating useful in indicating the combined effect of the environment but it also provides a framework to compare various site cured results.

The process as explained above is repeated for all the test elements by simply altering the raw climatic data to calculate the environmental rating in response to chloride conductivity. By using a revised scoring system and overall weighting factor the environmental rating with response to water sorptivity and oxygen permeability is also determined.

APPENDIX 10

STATISTICAL ANALYSIS OF CHLORIDE CONDUCTIVITY DATA FOR GGBS CONCRETES

STATISTICAL ANALYSIS OF CHLORIDE CONDUCTIVITY DATA FOR GGBS CONCRETES

			CHLORIDE CONDUCTIVITY RESULT - 28 days (mS/cm)						CHLORIDE CONDUCTIVITY RESULT - 90 days (mS/cm)					
			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SLAB SERIES ELEMENTS	ANALYSIS PER CURING METHOD	Cube												
		SA1	0.26				0.664		0.19				0.291	
		SA2	0.25				0.821		0.13				1.287	
		SA3	0.31			0.127			0.25			0.706		
		SA4	0.39			1.308			0.26			0.872		
		[illegible]	[illegible]	0.30	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Cast-in Control												
		SA1	0.36				0.732		0.22				0.755	
		SA2	0.33				0.940		0.20				0.970	
		SA3	0.62			1.124			0.37			0.863		
		SA4	0.54			0.553			0.37			0.863		
		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		[illegible]												
		SA1	0.36			0.182			0.18				0.810	
		SA2	0.25				0.960		0.17				0.918	
		SA3	0.29				0.545		0.33			0.810		
		SA4	0.47			1.323			0.34			0.918		
		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Hessian												
		SA1	0.35				0.768		0.31			0.431		
		SA2	0.41			0.202			0.20				1.165	
		SA3	0.48			1.354			0.30			0.259		
		SA4	0.35				0.768		0.53			0.776		
			[illegible]	[illegible]	0.00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		No Cure												
		SA1	0.35				0.837		0.31				0.229	
		SA2	0.34				0.894		0.17				1.296	
		SA3	0.65			0.866			0.47			0.991		
		SA4	0.65			0.866			0.41			0.554		
		[illegible]	[illegible]	0.50	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.34	[illegible]	[illegible]	[illegible]	[illegible]
	ANALYSIS ON ALL DATA	SA1:Cube	0.26				1.103		0.19				0.926	
		SA2:Cube	0.25				1.181		0.13				1.575	
		SA3:Cube	0.31				0.710		0.25				0.276	
		SA4:Cube	0.39				0.082		0.26				0.168	
		SA1:Cc	0.36				0.318		0.22				0.601	
		SA2:Cc	0.33				0.553		0.20				0.817	
		SA3:Cc	0.62			1.725			0.37			1.023		
		SA4:Cc	0.54			1.095			0.37			1.023		
		SA1:S	0.36				0.738		0.18				1.054	
		SA2:S	0.25				1.181		0.17				1.142	
		SA3:S	0.29				0.867		0.33			0.590		
		SA4:S	0.47			0.545			0.34			0.698		
		SA1:H	0.35				0.396		0.31			0.374		
		SA2:H	0.41			0.075			0.20				0.857	
		SA3:H	0.48			0.624			0.30			0.265		
		SA4:H	0.35				0.396		0.33			0.590		
		SA1:N	0.35				0.396		0.31			0.374		
		SA2:N	0.34				0.175		0.17				1.142	
		SA3:N	0.65			1.958			0.47			2.106		
		SA4:N	0.65			1.958			0.41			1.456		
		[illegible]	[illegible]	0.40	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
WALLS	ALL DATA	WA:Cube	0.33				1.272		0.24				1.227	
		WA:Cc	0.88			1.504			0.39			0.388		
		WA:F	0.52				0.313		0.32				0.566	
		WA:H	0.57				0.091		0.35				0.258	
		WA:N	0.61			0.141			0.49			1.161		
		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

APPENDIX 11

STATISTICAL ANALYSIS OF CHLORIDE CONDUCTIVITY DATA FOR FA CONCRETES

STATISTICAL ANALYSIS OF CHLORIDE CONDUCTIVITY DATA FOR FA CONCRETES

			CHLORIDE CONDUCTIVITY RESULT @ 28 days (mS/cm)						CHLORIDE CONDUCTIVITY RESULT @ 120 days (mS/cm)					
			Cl	Mean	SD	Tn	T1	5% SL	Cl	Mean	SD	Tn	T1	5% SL
SLAB SERIES ELEMENTS	ANALYSIS PER CURING METHOD	Cubes												
		SB1	0.42				0.578		0.17				0.590	
		SB2	1.43			1.456			0.12				[illegible]	
		SB3	0.49				0.529		0.31			1.517		
		SB4	0.61				0.272		0.31			0.547		
				0.74	0.468			1.481		0.23	0.097			1.481
		Curing Compound												
		SB1	0.99				0.168		0.40				[illegible]	
		SB2	1.53			1.228			0.58			1.336		
		SB3	0.59				1.202		0.42				0.590	
		SB4	1.17			0.112			0.47			0.031		
				1.06	0.387			1.481		0.47	0.081			1.481
		Sand												
		SB1	0.95				0.166		0.56			1.350		
		SB2	1.53			1.438			0.42			[illegible]		
		SB3	0.69				0.799		0.31				0.585	
		SB4	0.79				[illegible]		0.37				0.422	
				0.99	0.376			1.481		0.42	0.107			1.481
		Hessian												
		SB1	1.01				0.097		0.38				0.906	
		SB2	1.67			1.416			0.44			0.849		
		SB3	0.66				0.980		0.36				1.091	
		SB4	0.87				0.419		0.44			0.549		
				1.05	0.436			1.481		0.41	0.041			1.481
		No Cure												
		SB1	1.24				0.077		0.53			1.121		
		SB2	1.95			1.386			0.27				1.307	
		SB3	0.80				0.984		0.45			0.187		
		SB4	1.12				0.325		0.31					
				1.28	0.485			1.481		0.41	0.107			1.481
	ANALYSIS ON ALL DATA	SB1:Cube	0.42				1.423		0.17				1.852	
		SB2:Cube	1.43			0.965			0.12				2.254	
		SB3:Cube	0.49				1.258		0.31				0.647	
		SB4:Cube	0.61				0.975		0.31				0.647	
		SB1:Cc	0.99				0.077		0.40			0.129		
		SB2:Cc	1.55			1.199			0.58			1.681		
		SB3:Cc	0.59				1.022		0.42			0.302		
		SB4:Cc	1.11			0.207			0.47			0.733		
		SB1:S	0.95				0.171		0.56			1.509		
		SB2:S	1.55			1.199			0.42			0.302		
		SB3:S	0.69				0.786		0.31				0.647	
		SB4:S	0.79				0.549		0.37				0.129	
		SB1:H	1.01				0.030		0.38				0.045	
		SB2:H	1.67			1.530			0.44			0.474		
		SB3:H	0.66				0.856		0.36				0.216	
		SB4:H	0.87				0.360		0.44			0.474		
		SB1:N	1.24			0.514			0.53			1.250		
		SB2:N	1.95			2.191			0.27				0.991	
		SB3:N	0.80				0.526		0.45			0.388		
		SB4:N	1.12			0.230			0.31			0.216		
				1.02	0.423			2.709		0.39	0.116			2.709
WALLS	ALL DATA	WB:Cube	-						0.17				1.764	
		WB:Cc	-						0.71			0.548		
		WB:F	-						0.67			0.377		
		WB:H	-			-	-		0.62			0.206		
		WB:N	-			-	-		0.71			0.531		
				-	-	-	-	-		0.58	0.233			1.715

APPENDIX 12

STATISTICAL ANALYSIS OF CHLORIDE CONDUCTIVITY DATA FOR CSF CONCRETES

STATISTICAL ANALYSIS OF CHLORIDE CONDUCTIVITY DATA FOR CSF CONCRETES

			CHLORIDE CONDUCTIVITY RESULT @ 28 days (mS/cm)						CHLORIDE CONDUCTIVITY RESULT @ 120 days (mS/cm)					
			CI	Mean	SD	Tn	T1	5% SL	CI	Mean	SD	Tn	T1	
SLAB SERIES ELEMENTS	ANALYSIS PER CURING METHOD	Cubes												
		SC1	-						0.55				[illegible]	
		SC2	[illegible]			1.123			0.62				3.109	
		SC3	[illegible]				1.529		0.76			1.127		
		SC4	[illegible]				1.794		0.73			0.967		
				0.95	0.559			1.155		0.66	0.092			1.481
		Curing Cem. oum												
		SC1	-						[illegible]			0.286		
		SC2	1.85			[illegible]			0.75				1.222	
		SC3	1.16				[illegible]		1.21			1.170		
		SC4	1.04				[illegible]		0.94				2.234	
				1.35	0.437			1.155		0.99	0.192			1.481
		Sand												
		SC1	-						0.77				0.389	
		SC2	1.60			0.312			0.66				0.923	
		SC3	1.25			0.158			1.14			1.489		
		SC4	0.68				1.5[illegible]		0.83				0.687	
				1.18	0.164			1.155		0.85	0.206			1.484
		Hessian												
		SC1	-						1.06			0.842		
		SC2	1.56			0.952			0.57				1.533	
		SC3	1.17			0.01[illegible]			1.02			0.561		
		SC4	0.76				1.028		0.84				0.146	
				1.16	0.400			1.155		0.87	0.223			1.481
		No Cure												
		SC1	-						0.79				0.819	
		SC2	2.14			1.13			0.79				0.608	
		SC3	1.38				0.427		1.36			1.400		
		SC4	1.24				0.715		0.97				-0.026	
				1.59	0.484			1.155		0.96	0.264			[illegible]
	ANALYSIS ON ALL DATA	SC1:Cube	-						0.55				[illegible]	
		SC2:Cube	1.58			0.734			0.62				1.114	
		SC3:Cube	0.77				1.046		0.76				0.479	
		SC4:Cube	0.51				1.618		0.70				0.751	
		SC1:Ce	-						1.04			0.792		
		SC2:Ce	1.85			1.338			0.75				0.524	
		SC3:Ce	1.16				0.189		1.23			1.563		
		SC4:Ce	1.04				0.453		0.94			0.338		
		SC1:S	-						0.77				0.453	
		SC2:S	1.60			0.778			0.66				0.952	
		SC3:S	1.25			0.009			1.14			1.245		
		SC4:S	0.68				1.244		0.83				0.361	
		SC1:H	-						1.06			0.882		
		SC2:H	1.56			0.690			0.57				1.340	
		SC3:H	1.17				0.167		1.02			0.709		
		SC4:H	0.76				1.068		0.84				0.316	
		SC1:N	-						0.73				0.615	
		SC2:N	2.14			1.965			0.79				0.342	
		SC3:N	1.38			0.295			1.36			2.241		
		SC4:N	1.24				0.035		0.97			0.474		
				[illegible]	[illegible]			[illegible]		[illegible]	[illegible]			[illegible]
WALLS	ALL DATA	WC:Cube	-			-	-		0.79				1.590	
		WC:Ce	-			-	-		0.90				0.358	
		WC:S	-			-	-		0.97			0.426		
		WC:H	-			-	-		1.09			0.762		
		WC:N	-			-	-		1.09			0.762		
										[illegible]	[illegible]			1.715

APPENDIX 13

STATISTICAL ANALYSIS OF WATER SORPTIVITY DATA FOR GGBS CONCRETES

STATISTICAL ANALYSIS OF WATER SORPTIVITY DATA FOR GGBS CONCRETES

			WATER SORTIVITY RESULT @ 28 days (mm/h½)						WATER SORTIVITY RESULT @ 120 days (mm/h½)					
			WS	Mean	SD	To	T1	5% SL	WS	Mean	SD	To	T1	
SLAB SERIES ELEMENTS	ANALYSIS PER CURING METHOD	[illegible]												
		SA1	7.30			1.349			4.04				1.049	
		SA2	5.68				0.380		6.54			1.346		
		SA3	6.06			0.948			4.76				0.294	
		SA4	5.73				1.077		5.04				0.003	
				6.02	0.875			1.481		5.04	[illegible]			1.481
		Curing Cont.-und												
		SA1	7.78			1.065			5.47				1.347	
		SA2	7.24				3.153		6.87			1.071		
		SA3	6.79				1.259		6.24			0.171		
		SA4	7.40			2.238			6.20			0.106		
				7.30	0.409			1.481		6.12	[illegible]			1.481
		Sand												
		SA1	8.26			1.328			6.52			1.449		
		SA2	6.66				1.855		5.47				0.604	
		SA3	6.92				1.483		5.73				0.107	
		SA4	7.19				0.088		5.41				[illegible]	
				7.26	0.703			1.481		5.78	[illegible]			1.481
		Hessian												
		SA1	8.49			0.394			6.23			0.610		
		SA2	8.17				0.251		2.40				*1.494*	
		SA3	7.69				1.249		6.03			0.497		
		SA4	8.83			1.106			5.83			0.387		
				8.29	0.487			1.481		5.12	1.823			1.481
		No Cure												
		SA1	7.11				1.029		4.22				1.418	
		SA2	7.56				0.552		6.52			0.791		
		SA3	9.27			1.230			5.73			0.025		
		SA4	8.43			0.357			6.33			0.602		
				8.09	0.956			1.481		5.70	[illegible]			[illegible]
	ANALYSIS ON ALL DATA	SA1:Cube	7.28				0.187		4.04				1.421	
		SA2:Cube	5.68				1.640		6.34			0.736		
		SA3:Cube	6.06				1.279		4.76				0.741	
		SA4:Cube	5.83				2.475		5.04				0.479	
		SA1:Cc	7.78			0.372			5.17				0.357	
		SA2:Cc	7.24				0.546		6.87			1.238		
		SA3:Cc	6.79				0.577		6.24			0.645		
		SA4:Cc	7.40			0.008			6.20			0.602		
		SA1:S	8.26			0.832			6.52			0.903		
		SA2:S	6.66				0.707		5.47				0.076	
		SA3:S	6.92				0.457		5.73			0.162		
		SA4:S	7.19				0.190		5.41				0.737	
		SA1:H	8.49			1.050			6.23			0.628		
		SA2:H	8.17			0.749			2.40				*2.957*	
		SA3:H	7.69			0.282			6.03			0.434		
		SA4:H	8.83			1.383			5.83			0.256		
		SA1:N	7.11				0.275		4.22				1.250	
		SA2:N	7.56			0.164			6.52			0.910		
		SA3:N	9.27			1.800			5.73			0.161		
		SA4:N	8.43			0.992			6.33			0.725		
				7.40	1.042			2.709		[illegible]	[illegible]			[illegible]
WALLS	ALL DATA	WA Cube	8.50				1.581		5.00				1.593	
		WA Cc	10.70				0.190		7.60			0.177		
		WA.F	12.30			0.822			8.40			0.722		
		WA H	11.10			0.063			7.00				0.231	
		WA N	12.40			0.585			8.70			0.926		
				[illegible]	[illegible]			[illegible]		[illegible]	[illegible]			[illegible]

APPENDIX 14

STATISTICAL ANALYSIS OF WATER SORPTIVITY DATA FOR FA CONCRETES

STATISTICAL ANALYSIS OF WATER SORPTIVITY DATA FOR FA CONCRETES

			WATER SORPTIVITY RESULT @ 28 days (mm/h½)						WATER SORPTIVITY RESULT @ 120 days (mm/h½)					
			WS	Mean	SD	Tn	T1	5% SL	WS	Mean	SD	Tn	T1	
SLAB SERIES ELEMENTS	ANALYSIS PER CURING METHOD	Cubes												
		SB1	6.53			1.293			3.65				1.003	
		SB2	5.63				2.132		4.96			0.67		
		SB3	4.98				1.148		5.23			1.08		
		SB4	5.71				2.011		3.90				2.289	
				5.71	0.636			1.481		4.43	0.780			1.481
		Curing Compound												
		SB1	10.23			1.459			5.92			1.226		
		SB2	7.04				0.801		5.07				0.636	
		SB3	7.82				0.248		4.92				0.973	
		SB4	7.59				0.409		5.54			0.382		
				8.17	1.412			1.481		5.36	0.450			1.481
		Sand												
		SB1	8.43			0.823			4.30				0.706	
		SB2	8.05			0.588			5.80			1.335		
		SB3	4.89				1.405		5.07			0.196		
		SB4	7.11				0.005		4.42				0.825	
				7.12	1.598			1.481		4.95	[illegible]			1.481
		Hessian												
		SB1	8.39			0.867			5.75			1.283		
		SB2	8.26			0.756			4.89				0.466	
		SB3	6.08				1.225		5.22			0.217		
		SB4	6.97				2.588		4.58				1.053	
				7.41	1.135			1.481		5.11	[illegible]			1.481
		No Cure												
		SB1	9.96			194			5.44			0.632		
		SB2	8.79			0.399			5.43			0.609		
		SB3	6.61				1.068		5.24			0.233		
		SB4	7.42				8.524		4.42				1.475	
				8.20	1.482			1.481		5.13				[illegible]
	ANALYSIS ON ALL DATA	SB1:Cube	6.53				0.532		3.65				2.216	
		SB2:Cube	5.63				1.143		4.96				0.068	
		SB3:Cube	4.98				1.579		5.23			0.388		
		SB4:Cube	5.71				1.091		3.90				1.807	
		SB1:Cc	10.23			1.965			5.92			1.517		
		SB2:Cc	7.04				0.190		5.07			0.126		
		SB3:Cc	7.82			0.337			4.92				0.125	
		SB4:Cc	7.59			0.184			5.54			0.887		
		SB1:S	8.43			0.746			4.30				0.820	
		SB2:S	8.05			0.495			5.80			1.316		
		SB3:S	4.89				1.645		5.07			0.124		
		SB4:S	7.11				0.141		4.42				0.944	
		SB1:H	8.39			0.722			5.75			1.238		
		SB2:H	8.26			0.636			4.89				0.179	
		SB3:H	6.08				0.889		5.22			0.364		
		SB4:H	6.97				0.240		4.58				0.677	
		SB1:N	9.96			1.783			5.44			0.721		
		SB2:N	8.79			0.989			5.43			0.703		
		SB3:N	6.61				0.477		5.24			0.404		
		SB4:N	7.42			0.867			4.42				0.952	
				7.32	1.382			2.709		5.09				2.709
WALLS	ALL DATA	WB:Cube	4.40				1.598		3.80				1.558	
		WB:Cc	8.20			0.178			7.90			0.997		
		WB:F	7.80				0.009		5.70				0.374	
		WB:H	8.40			0.271			7.10			0.499		
		WB:N	10.30			1.159			7.00			0.436		
				7.82	2.141			1.715		6.30	[illegible]			1.715

APPENDIX 15

STATISTICAL ANALYSIS OF WATER SORPTIVITY DATA FOR CSF CONCRETES

STATISTICAL ANALYSIS OF WATER SORPTIVITY DATA FOR CSF CONCRETES

			WATER SORTIVITY RESULT @ 28 days (mm/h½)						WATER SORTIVITY RESULT @ [illegible] days (mm/h½)					
			WS	Mean	SD	Tn	T1	5% SL	WS	Mean	SD	Tn	T1	5% SL
SLAB SERIES ELEMENTS	ANALYSIS PER CURING METHOD	Cubes												
		SC1	7.20			1.278			–					
		SC2	6.52			0.223			6.12			1.141		
		SC3	5.70				1.060		5.32				0.419	
		SC4	6.10				0.439		5.16				0.722	
				6.38	0.613			1.481		5.55	0.512			1.153
		Curing [illegible]												
		SC1	9.33			0.496			7.04				0.022	
		SC2	6.36				1.151		7.23			0.141		
		SC3	9.64			0.661			8.46			1.160		
		SC4							5.52				1.270	
				8.44	1.507			1.155		7.06	1.203			1.454
		[illegible]												
		SC1	6.82				0.943		[illegible]				1.262	
		SC2	7.42				0.105		7.24			1.073		
		SC3	8.24			1.049			6.72			0.439		
		SC4	–						6.16				0.250	
				7.49	0.747			1.155		6.36	0.817			1.484
		Hessian												
		SC1	8.57			0.918			6.34				0.011	
		SC2	6.56				0.994		6.20				0.715	
		SC3	8.41			0.780			6.20				0.692	
		SC4	5.83				0.724		5.65			1.425		
				7.59	1.041			1.481		6.35	0.214			1.481
		No Cure												
		SC1	6.14				[illegible]		[illegible]				0.986	
		SC2	8.27			1.117			[illegible]				0.028	
		SC3	9.01			[illegible]			[illegible]			[illegible]		
		SC4	–											
				7.80	1.491			1.155		6.16	1.266			1.155
	ANALYSIS ON ALL DATA	SC1:Cube	7.20				0.774		–					
		SC2:Cube	6.52				0.779		6.12				0.243	
		SC3:Cube	5.70				1.438		5.32				1.097	
		SC4:Cube	6.10				1.116		5.16				1.263	
		SC1:Cc	9.33			1.496			7.04			0.741		
		SC2:Cc	6.36				0.900		7.23			0.950		
		SC3:Cc	9.64			1.745			8.46			2.260		
		SC4:Cc	–						5.52				0.876	
		SC1.S	6.82				0.534		5.13				1.079	
		SC2:S	7.42				0.049		7.24			0.960		
		SC3:S	8.24			0.519			6.72			0.407		
		SC4.S	–						6.16				0.195	
		SC1:H	8.57			0.883			6.34			0.002		
		SC2:H	6.56				0.741		6.20				0.156	
		SC3:H	8.41			0.752			6.20				0.154	
		SC4:H	6.84				0.514		6.65			0.324		
		SC1.N	6.14				1.084		4.81				1.634	
		SC2.N	8.27			0.643			6.12				0.235	
		SC3.N	9.01			1.217			7.55			1.286		
		SC4.N												
				7.48	1.237			2.620		6.34	[illegible]			[illegible]
WALLS	ALL DATA	WC:Cube	6.60				1.613		5.00				1.327	
		WC:Cc	9.10			0.984			6.50				0.156	
		WC:F	8.50			0.356			6.80			0.078		
		WC:H	5.60			0.460			5.00			1.484		
		WC:N	5.60				0.167		5.50				0.078	
				8.16	0.950			1.713		6.29	1.201			1.715

APPENDIX 16

STATISTICAL ANALYSIS OF OXYGEN PERMEABILTY INDEX DATA FOR GGBS CONCRETES

STATISTICAL ANALYSIS OF OXYGEN PERMEABILITY DATA FOR GGBS CONCRETES

			(PAr) COEFFICIENT OF PERMEABILITY @ 28 days					(PAr) COEFFICIENT OF PERMEABILITY @ 520 days					
		k	Mean	SD	Tn	T1	95% SL	k	[illegible]	SD	Tn	T1	95% SL
SLAB SERIES ELEMENTS – ANALYSIS PER CURING METHOD	[illegible]												
	SA1	[illegible]			0.763			4.628E-10			[illegible]		
	SA2	1.924E-10				1.462		2.056E-10				[illegible]	
	SA3	3.095E-10			0.792			2.342E-10				[illegible]	
	SA4	2.893E-10			[illegible]			1.723E-10				[illegible]	
			[illegible]	[illegible]			1.481		[illegible]	1.398E-10			1.481
	Curing												
	SA1	[illegible]				[illegible]		[illegible]				[illegible]	
	SA2	[illegible]				1.299		1.809E-10				[illegible]	
	SA3	[illegible]			1.097			3.558E-10			0.796		
	SA4	[illegible]			0.312			3.652E-10			[illegible]		
			[illegible]	3.239E-10			1.481		2.525E-10	[illegible]			1.481
	[illegible]												
	SA1	1.593E-10						1.242E-10				[illegible]	
	SA2	1.873E-10				0.793		1.354E-10				[illegible]	
	SA3	[illegible]			[illegible]			2.251E-10			[illegible]		
	SA4	[illegible]			[illegible]			2.866E-10			[illegible]		
			2.758E-10	[illegible]			[illegible]		[illegible]	[illegible]			1.481
	[illegible]												
	SA1	[illegible]			1.196			1.820E-10				0.333	
	SA2	[illegible]				1.083		1.572E-10				1.009	
	SA3	[illegible]			0.385			2.024E-10				0.025	
	SA4	[illegible]				0.498		2.948E-10			1.368		
			[illegible]	[illegible]			[illegible]		[illegible]	[illegible]			[illegible]
	[illegible]												
	SA1	[illegible]			1.029			[illegible]				[illegible]	
	SA2	[illegible]				[illegible]		1.381E-10				[illegible]	
	SA3	[illegible]			0.711			3.598E-10			[illegible]		
	SA4	[illegible]			[illegible]			[illegible]			[illegible]		
			[illegible]	[illegible]			1.481		[illegible]	1.142E-10			1.481
SLAB SERIES ELEMENTS – ANALYSIS ON ALL DATA	SA1 Cube	2.821E-10				0.810		4.628E-10			2.339		
	SA2 Cube	1.924E-10				1.070		2.056E-10				0.243	
	SA3 Cube	3.095E-10				0.480		2.342E-10			0.947		
	SA4 Cube	2.893E-10				0.582		1.723E-10				0.599	
	SA1:Cc	4.971E-10			0.463			5.012E-10				1.273	
	SA2:Cc	2.145E-10				0.860		1.809E-10				0.403	
	SA3:Cc	7.640E-10			1.507			[illegible]			1.264		
	SA4:Cc	5.975E-10			0.969			3.652E-10			1.339		
	SA1:S	1.593E-10				1.337		1.242E-10				1.062	
	SA2:S	1.873E-10				1.095		1.354E-10				0.950	
	SA3:S	4.959E-10				[illegible]		2.251E-10				0.049	
	SA4:S	3.528E-10				0.363		2.866E-10			0.968		
	SA1:H	7.104E-10			1.537			1.820E-10				0.482	
	SA2:H	2.006E-10				1.020		1.572E-10				0.932	
	SA3:H	5.291E-10			0.624			2.024E-10				0.277	
	SA4:H	3.364E-10				0.371		2.948E-10			0.650		
	SA1:N	7.266E-10			1.619			1.523E-10				0.992	
	SA2:N	2.524E-10				0.869		1.381E-10				0.923	
	SA3:N	5.587E-10			0.721			3.598E-10			1.334		
	SA4:N	[illegible]			[illegible]			[illegible]			[illegible]		
			[illegible]	[illegible]			[illegible]		[illegible]	[illegible]			[illegible]
WALLS	WA:Cube	1.032E-09				[illegible]		[illegible]				[illegible]	
	WA:Cc	1.670E-09			[illegible]			[illegible]				[illegible]	
	WA:F	1.136E-09				[illegible]		[illegible]			[illegible]		
	WA:Sl	[illegible]			[illegible]			[illegible]				[illegible]	
	WA:N	8.996E-10				[illegible]		[illegible]			[illegible]		
			[illegible]	[illegible]			[illegible]		[illegible]	[illegible]			[illegible]

APPENDIX 17

STATISTICAL ANALYSIS OF OXYGEN PERMEABILTY INDEX DATA FOR FA CONCRETES

STATISTICAL ANALYSIS OF OXYGEN PERMEABILITY DATA FOR FA CONCRETES

SLAB SERIES ELEMENTS – ANALYSIS PER CURING METHOD	SB1							5.879E-11				1.466	
	SB2	5.530E-11				0.707		9.734E-11			3.152		
	SB3							1.181E-10			5.971		
	SB4	7.364E-10			0.707			1.039E-12			3.367		
	SB1	-						9.117E-10			2.087		
	SB2	1.462E-10				0.707		7.243E-11				1.236	
	SB3	-						1.534E-12			3.080		
	SB4	5.508E-10			0.707			1.389E-12			3.160		
	SB1	-						9.198E-11				1.319	
	SB2	1.254E-10				3.095		1.347E-10			0.436		
	SB3	8.351E-11				0.950		1.845E-10			1.174		
	SB4	3.808E-10			1.040			1.173E-10				0.481	
	SB1	-						1.367E-10			0.965		
	SB2	1.533E-10				0.707		7.160E-11				1.298	
	SB3	-						1.857E-10			1.341		
	SB4	2.579E-10			0.707			1.353E-10			0.364		
	SB1	-						2.256E-10				0.917	
	SB2	1.463E-10				0.516		8.032E-11				0.770	
	SB3	1.377E-10				0.636		1.957E-10			1.436		
	SB4	2.612E-10			0.857			8.749E-11				0.633	
SLAB SERIES ELEMENTS – ANALYSIS ON ALL DATA	SB1:Cube	-						5.868E-11				1.316	
	SB2:Cube	6.559E-11				0.576		9.734E-11				0.635	
	SB3:Cube	-						1.161E-10				5.154	
	SB4:Cube	1.384E-10				0.451		3.038E-10				0.511	
	SB1:Cc	-						2.137E-10			1.983		
	SB2:Cc	1.462E-10				0.287		7.243E-11				1.202	
	SB3:Cc	-						1.538E-10			0.598		
	SB4:Cc	5.099E-10			2.872			1.589E-10			0.711		
	SB1:S							9.198E-11				0.734	
	SB2:S	1.254E-10				0.437		1.347E-10			0.617		
	SB3:S	8.351E-11				0.902		1.849E-10			1.286		
	SB4:S	1.810E-10				0.901		1.173E-10				0.204	
	SB1:H	-						1.367E-10			0.217		
	SB2:H	1.533E-10				0.389		7.155E-11				1.225	
	SB3:H	-						1.856E-10			1.001		
	SB4:H	2.579E-10			0.220			1.353E-10			0.187		
	SB1:N	-						2.254E-10				0.143	
	SB2:N	1.463E-10				0.289		8.037E-11				1.031	
	SB3:N	1.377E-10				0.557		1.957E-10			1.526		
	SB4:N	2.612E-10			0.357			8.749E-11				0.873	
WALLS	WB:Cube	7.094E-11				1.550		4.902E-11				2.040	
	WB:Cc	6.115E-10			0.836			4.235E-10			1.485		
	WB:S	3.241E-10				0.457		8.528E-11				0.852	
	WB:H	5.457E-10			0.551			3.442E-10			0.235		
	WB:N	1.590E-10			0.602			2.269E-10			0.122		

APPENDIX 18

STATISTICAL ANALYSIS OF OXYGEN PERMEABILTY INDEX DATA FOR CSF CONCRETES

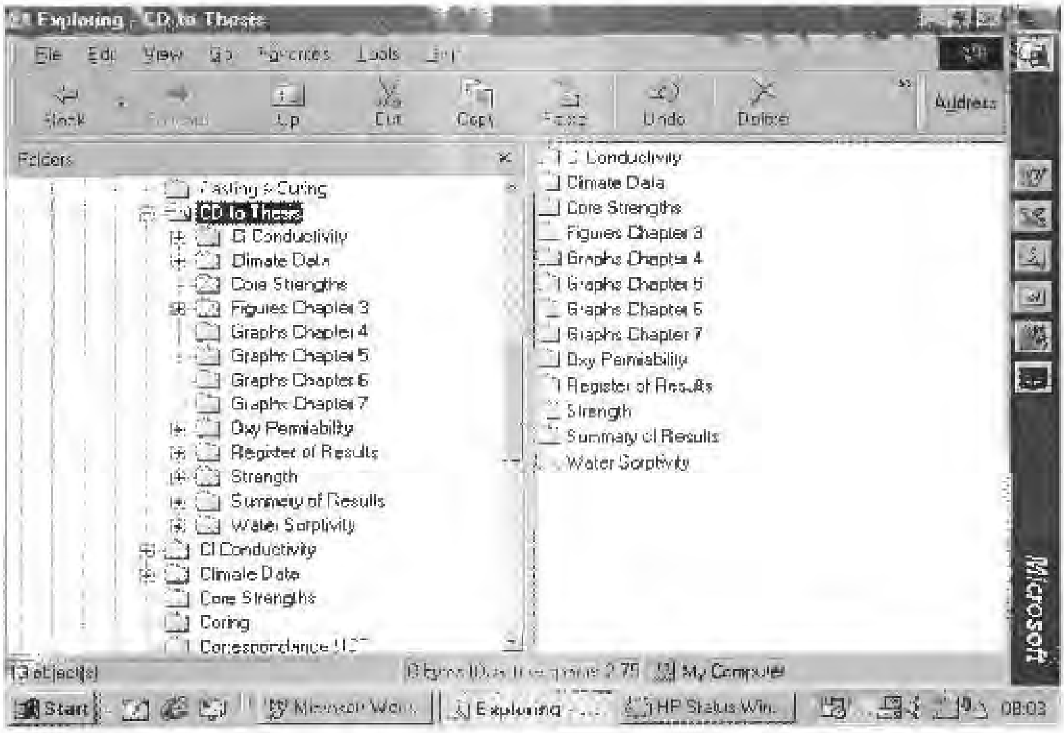
STATISTICAL ANALYSIS OF OXYGEN PERMEABILITY DATA FOR CSF CONCRETES

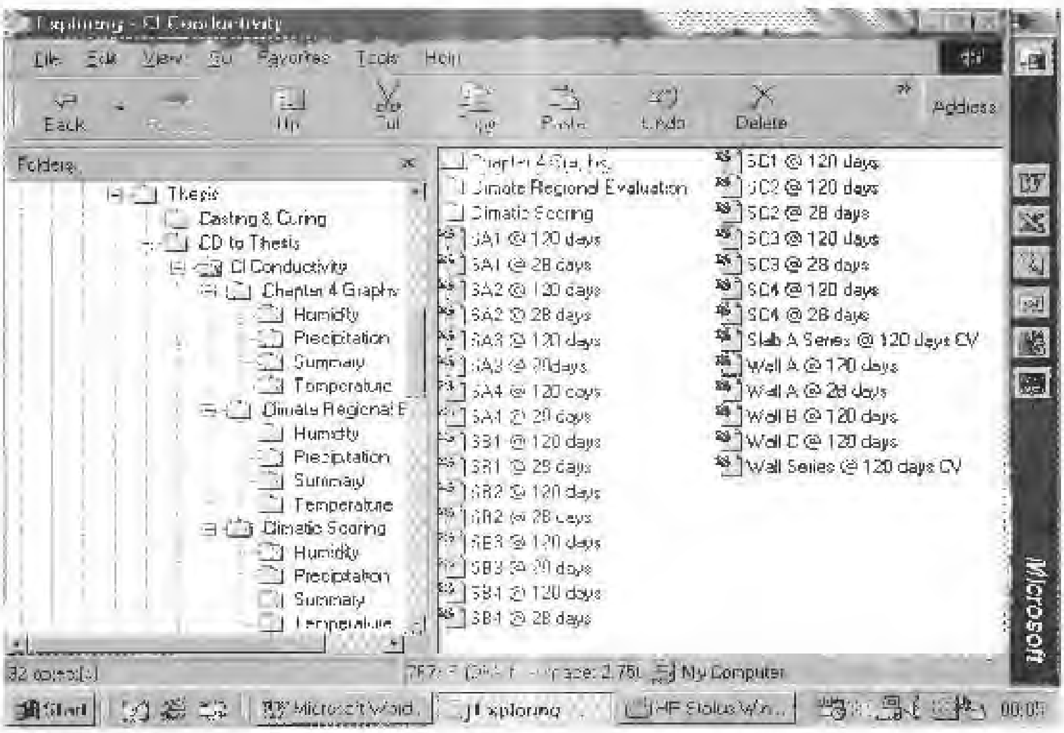
		Oxygen COEFFICIENT OF PERMEABILITY @ 28 days						Oxygen COEFFICIENT OF PERMEABILITY @ 120 days					
			[illegible]	SD	Tp	Tt	5% SL	k	Mean	SD	Tp	Tt	5% SL
SLAB SERIES ELEMENTS – ANALYSIS PER CURING METHOD	[illegible]												
	SC1							-					
	SC2	9.658E-11				[illegible]		1.156E-10				0.486	
	SC3	1.690E-10			0.997			1.720E-10			1.150		
	SC4	2.412E-10			0.998			1.516E-10				[illegible]	
			1.429E-10	4.628E-11			4.159		[illegible]	[illegible]			2.450
	[illegible]												
	SC1							[illegible]			1.0[illegible]		
	SC2	1.413E-10				0.996		8.262E-11				1.021	
	SC3	4.620E-10			1.[illegible]			3.035E-10			0.613		
	SC4	2.929E-10				[illegible]		1.090E-10				0.656	
			[illegible]	[illegible]			1.13[illegible]		[illegible]	1.338E-10			1.481
	[illegible]												
	SC1							2.245E-10			0.306		
	SC2	1.191E-10				0.707		1.011E-10				1.103	
	SC3							3.379E-10			0.452		
	SC4	2.329E-10			[illegible]			2.499E-10			[illegible]		
			1.760E-10	5.[illegible]E-11					2.[illegible]E-10	[illegible]E-11			1.481
	[illegible]												
	SC1							[illegible]			[illegible]		
	SC2	[illegible]				1.031		9.117E-11				1.383	
	SC3	[illegible]			1.[illegible]			[illegible]				[illegible]	
	SC4	[illegible]			[illegible]			[illegible]			[illegible]		
			4.[illegible]E-10	2.240E-10			1.[illegible]39		2.[illegible]E-10	[illegible]			[illegible]
	[illegible]												
	SC1	-						[illegible]				[illegible]	
	SC2	1.283E-10				1.066		2.017E-10			0.971		
	SC3	7.6[illegible]E-10			[illegible]			1.560E-10				0.930	
	SC4	5.12[illegible]E-10			[illegible]			-					
			[illegible]	1.5[illegible]E-10			1.1[illegible]		1.5[illegible]E-10	2.[illegible]E-11			[illegible]
SLAB SERIES ELEMENTS – ANALYSIS ON ALL DATA	SC1:Cube							-					
	SC2:Cube	9.658E-11				1.029		1.010E-10				1.308	
	SC3:Cube	1.690E-10				0.496		1.720E-10				0.502	
	SC4:Cube	1.412E-10				0.755		1.036E-10				1.092	
	SC1:Cu	-						1.590E-10			1.941		
	SC2:Cu	1.213E-10				0.838		8.262E-11				1.022	
	SC3:Cu	4.620E-10			5.042			1.095E-10			1.497		
	SC4:Cu	2.930E-10			0.078			2.360E-10				0.781	
	SC1:S	-						2.245E-10			0.306		
	SC2:S	1.191E-10				0.891		1.012E-10				1.111	
	SC3:S	-						3.579E-10			0.459		
	SC4:S	2.329E-10				0.249		2.499E-10			0.586		
	SC1:H	-						1.569E-10			1.579		
	SC2:H	1.133E-10				0.925		9.115E-11				1.225	
	SC3:H	5.587E-10			5.580			2.362E-10			0.429		
	SC4:H	5.501E-10			1.350			2.960E-10			1.513		
	SC1:N	-						1.735E-10				0.239	
	SC2:N	1.283E-10				0.829		2.017E-10			0.096		
	SC3:N	7.624E-10			0.491			1.561E-10				0.310	
	SC4:N	[illegible]			[illegible]			-					
			2.773E-10	1.7[illegible]E-10			2.0[illegible]		[illegible]	5.[illegible]E-11			2.0[illegible]
WALLS – ALL DATA	WC:Cube	1.641E-10				1.730		1.085E-10				1.687	
	WC:Cu	3.651E-10			1.542			3.368E-10			0.777		
	WC:S	2.729E-10			0.157			3.337E-10			0.722		
	WC:H	2.507E-10				0.080		2.820E-10			0.175		
	WC:N	2.166E-10				0.550		2.659E-10			0.911		
			2.5[illegible]E-10	8.255E-11									

APPENDIX 19

ATTACHED CD ROM WITH DATA IN ELECTRONIC FORMAT

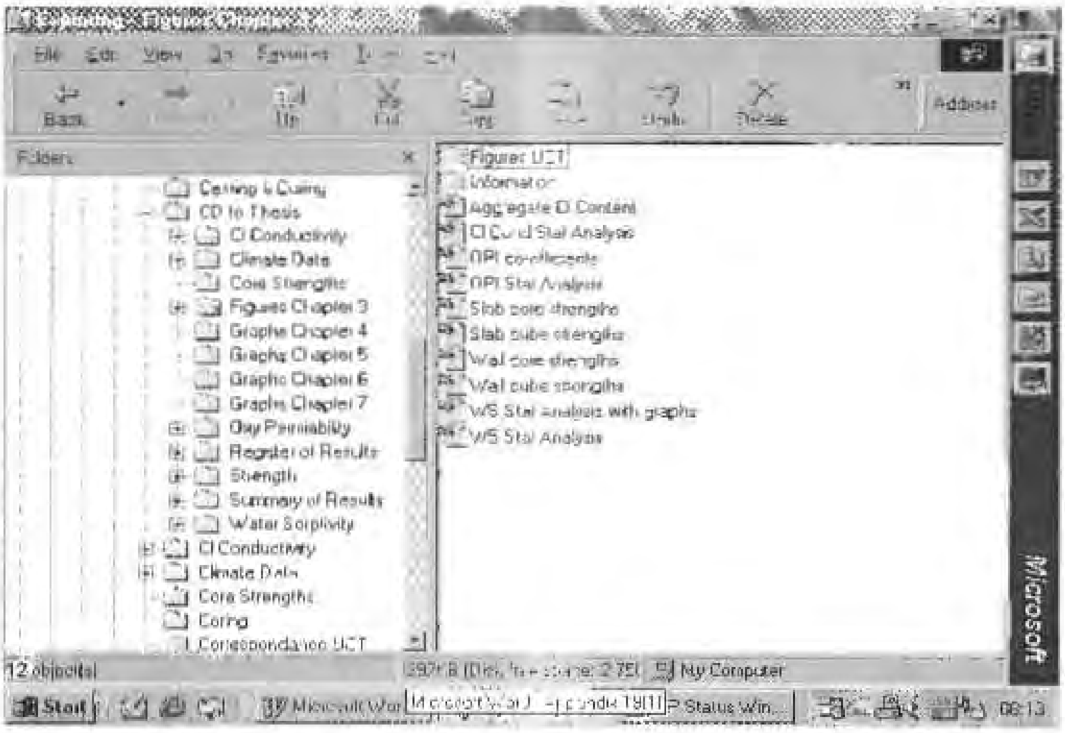
The Images below give an explored view of the folders and files contained in the CD ROM attached in the back sleeve of this document.






Exploring - Climate Data
File Edit View Go Favorites Tools Help
Back Up Cut Copy Paste Undo Delete Address
Folders
Casting & Curing
CD to Thesis
Cl Conductivity
Climate Data
Humidity
Precipitation
Temperature
Core Strengths
Figures Chapter 3
Figures UCT
Information
Graphs Chapter 4
Graphs Chapter 5
Graphs Chapter 6
Graphs Chapter 7
Oxy Permeability
Register of Results
Strength
Summary of Results
Water Sorptivity
Humidity
Precipitation
Temperature
3 object(s)
My Computer
Start
Microsoft Word...
Exploring
HP Status Win...
08:10
Microsoft


Exploring - Core Strengths
File Edit View Go Favorites Tools Help
Back Up Cut Copy Paste Undo Delete Address
Folders
Casting & Curing
CD to Thesis
Cl Conductivity
Climate Data
Core Strengths
Figures Chapter 3
Graphs Chapter 4
Graphs Chapter 5
Graphs Chapter 6
Graphs Chapter 7
Oxy Permeability
Register of Results
Strength
Summary of Results
Water Sorptivity
Cl Conductivity
Climate Data
Core Strengths
Coring
Correspondance UCT
Slab A series
Slab B series
Slab C series
Wall series
4 object(s)
My Computer
Start
Microsoft Word...
Exploring
HP Status Win...
08:12
Microsoft


Back
Delete
Address
Folders
Casting & Curing
CD to Thesis
Cl Conductivity
Climate Data
Core Strengths
Figures Chapter 3
Graphs Chapter 4
Graphs Chapter 5
Graphs Chapter 6
Graphs Chapter 7
Gay Permeability
Register of Results
Strength
Summary of Results
Water Sorptivity
Cl Conductivity
Climate Data
Core Strengths
Curing
Correspondance UCT
Figures UCT
Aggregate Cl Content
Cl Cond Stat Analysis
OPI Stat Analysis
Slab core strengths
Slab cube strengths
Wall core strengths
Wall cube strengths
WS Stat analysis with graphs
WS Stat Analysis
12 object(s)
My Computer
Start
Status Win...
Microsoft


Exploring - Graphs Chapter 4
File
Edit
View
Go
Favorites
Tools
Help
Back
Up
Cut
Copy
Undo
Delete
Address
Folders
Casting & Curing
CD to Thesis
Cl Conductivity
Climate Data
Core Strengths
Figures Chapter 3
Graphs Chapter 4
Graphs Chapter 5
Graphs Chapter 6
Graphs Chapter 7
Register of Results
Strength
Summary of Results
Water Sorptivity
Cl Conductivity
Climate Data
Core Strengths
Curing
Correspondance UCT
Precipitation Model
Temperature Model
3 object(s)
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Start
Microsoft Word
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HP Status Win...
08:14
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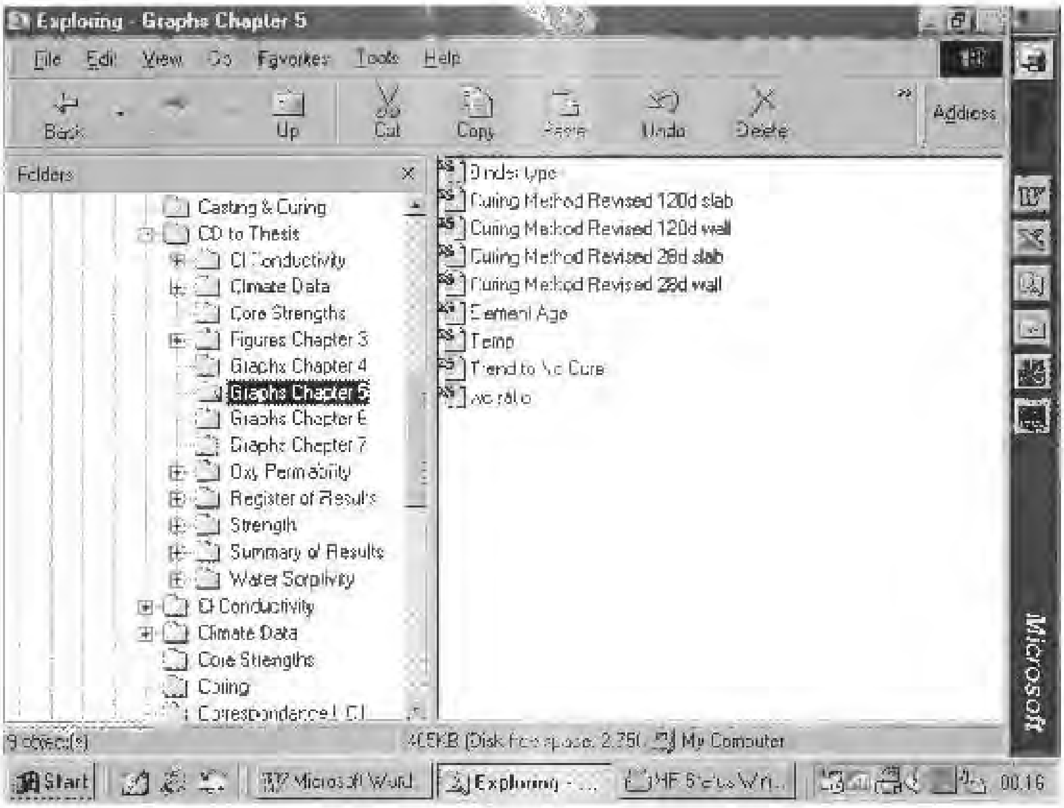
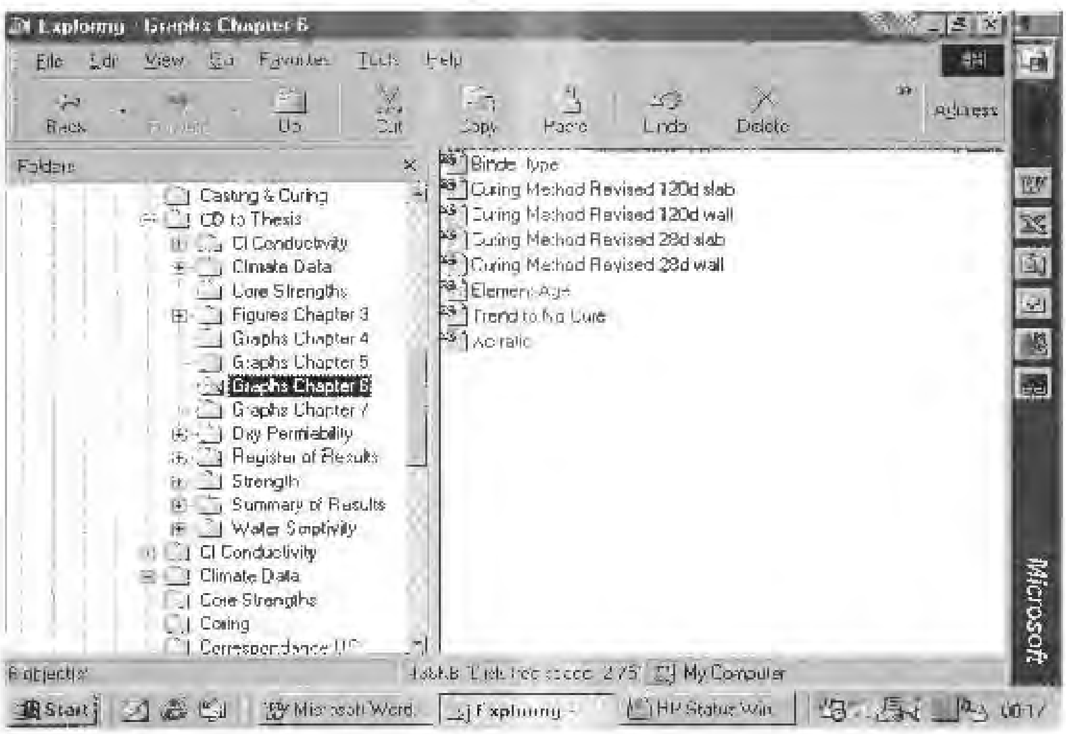
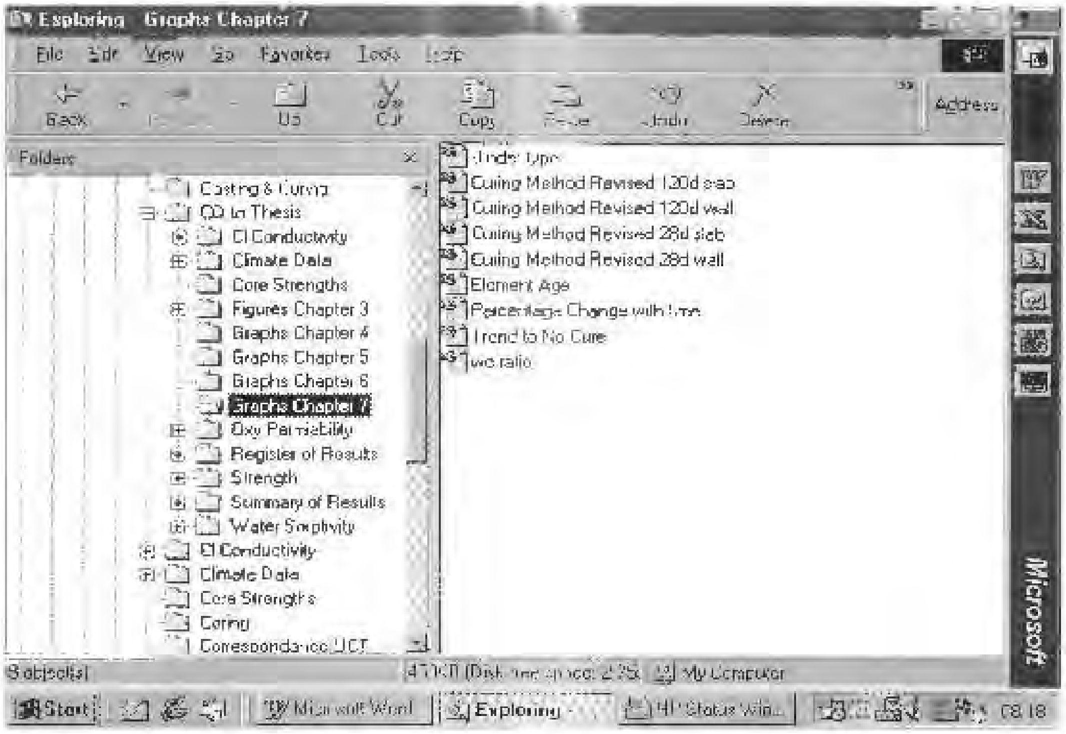
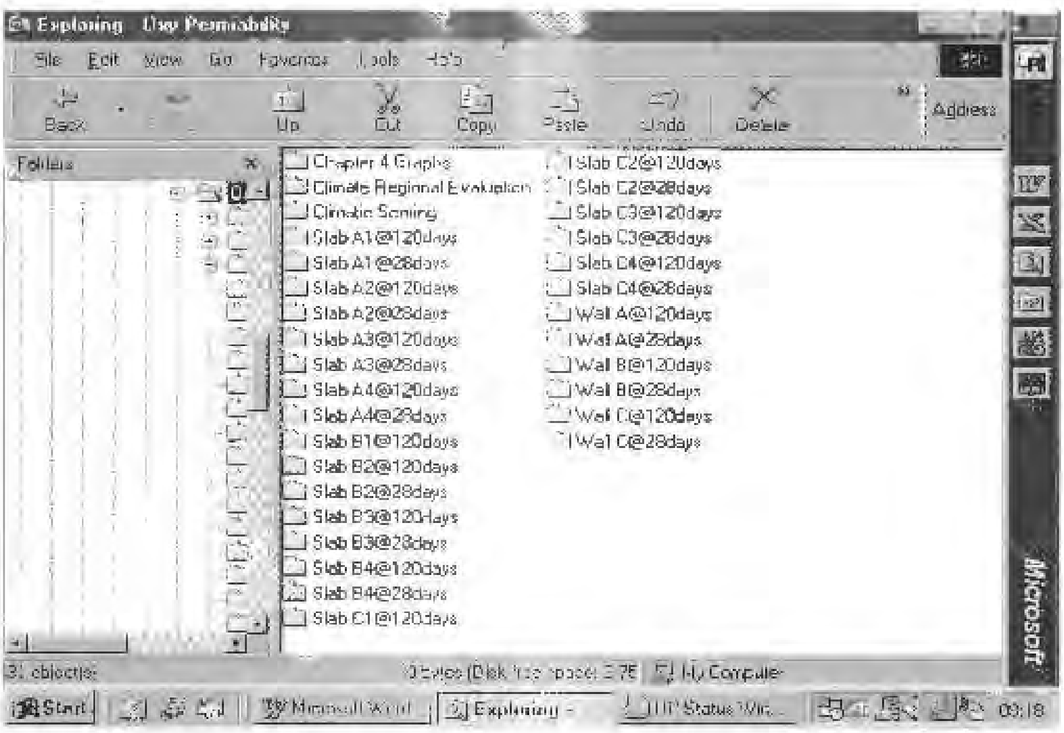
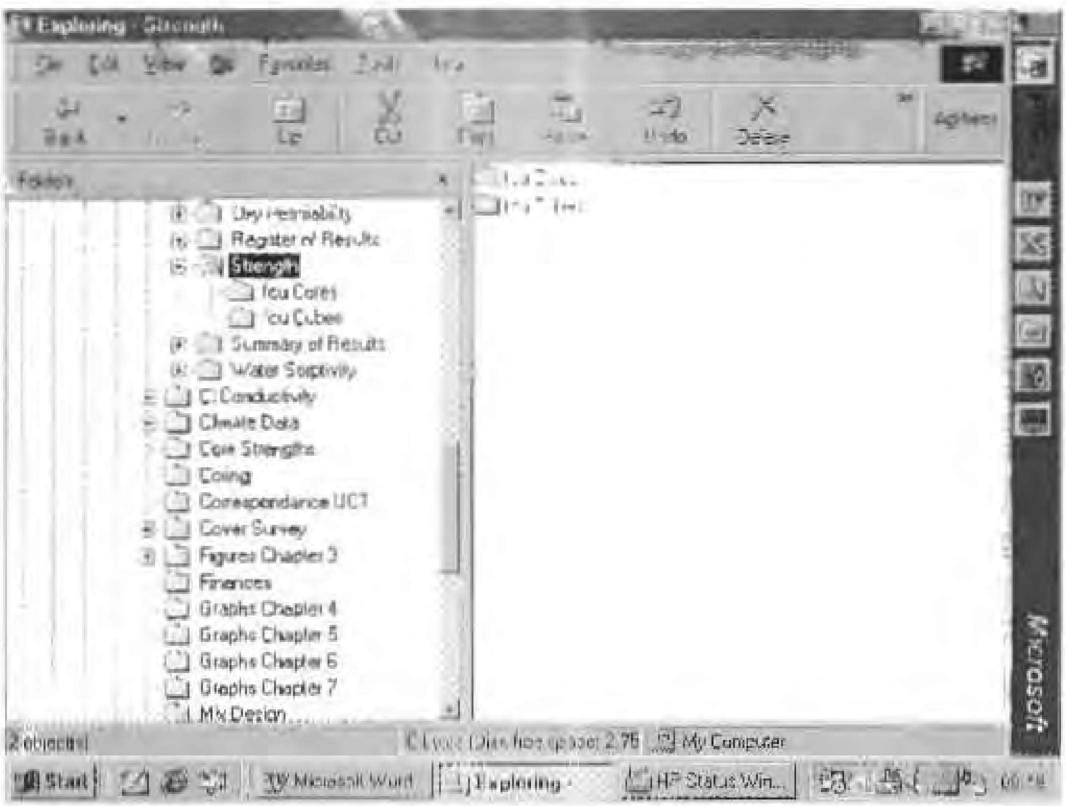
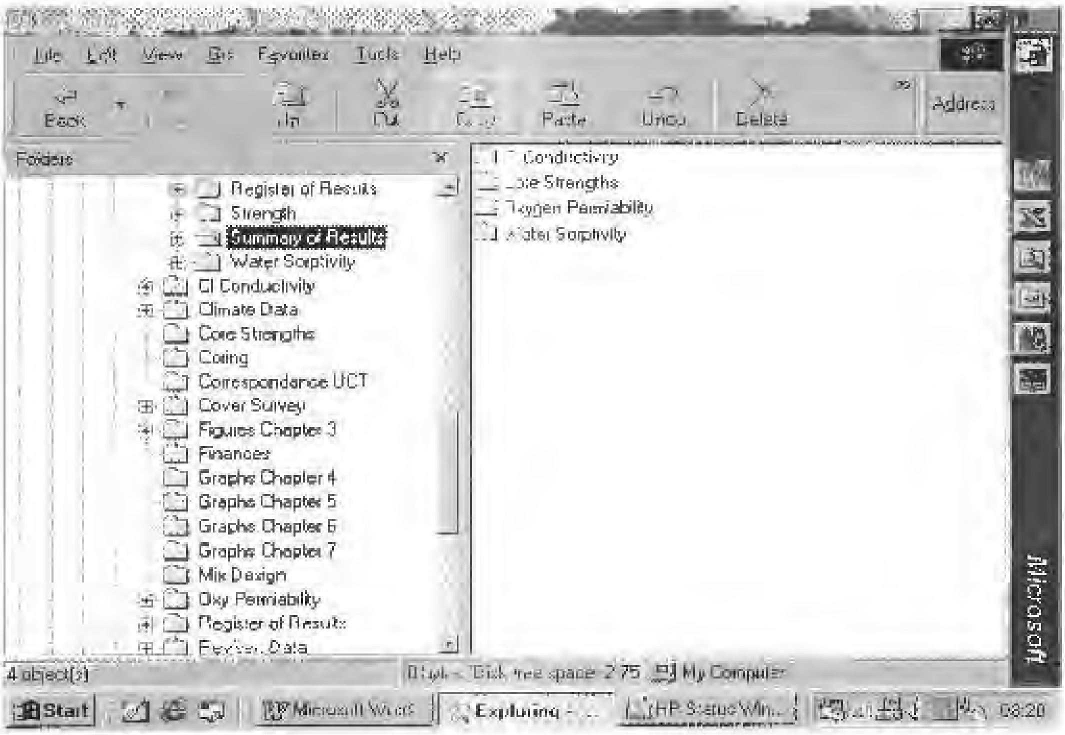

Exploring - Graphs Chapter 5
Folders
Casting & Curing
CD to Thesis
Cl Conductivity
Climate Data
Core Strengths
Figures Chapter 3
Graphs Chapter 4
Graphs Chapter 5
Graphs Chapter 6
Graphs Chapter 7
Strength
Summary of Results
Water Sorptivity
Binder type
Curing Method Revised 120d slab
Curing Method Revised 120d wall
Curing Method Revised 28d slab
Curing Method Revised 28d wall
Temp
My Computer
Microsoft

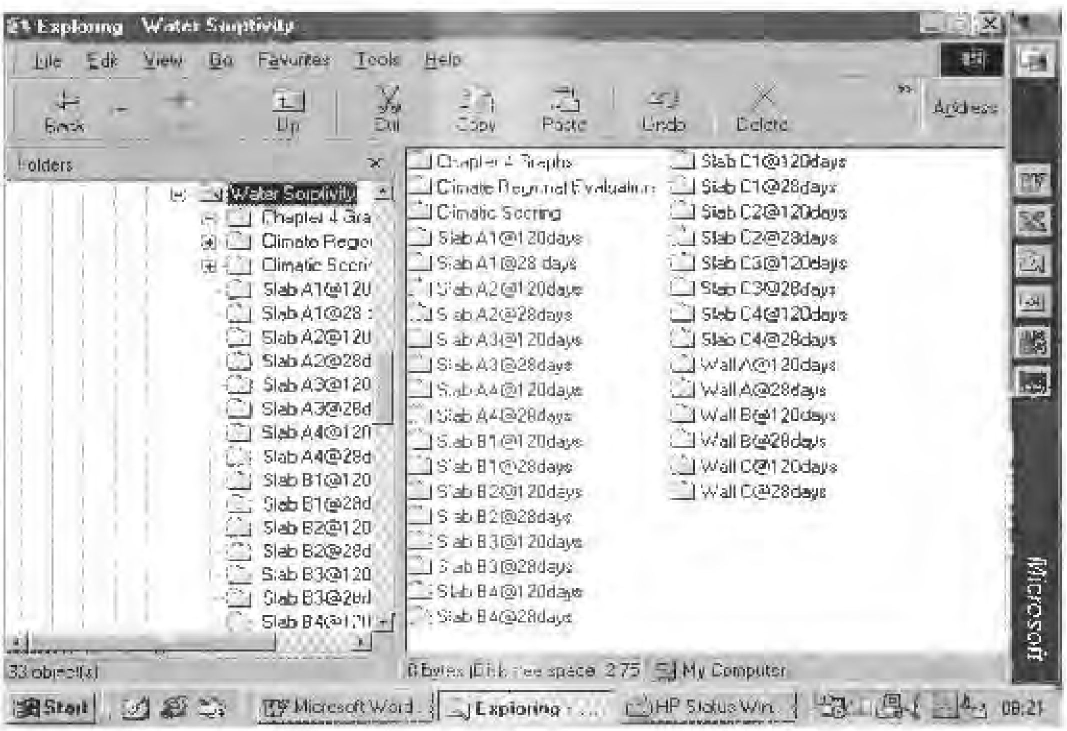

Exploring - Graphs Chapter 6
Folders
Casting & Curing
CD to Thesis
Cl Conductivity
Climate Data
Core Strengths
Figures Chapter 3
Graphs Chapter 4
Graphs Chapter 5
Graphs Chapter 6
Strength
Summary of Results
Curing Method Revised 120d slab
Curing Method Revised 120d wall
Curing Method Revised 28d slab
Curing Method Revised 28d wall
My Computer
Microsoft


Exploring - Graphs Chapter 7
File
Edit
View
Go
Favorites
Tools
Help
Back
Up
Cut
Copy
Paste
Undo
Delete
Address
Folders
Casting & Curing
CD to Thesis
Cl Conductivity
Climate Data
Core Strengths
Figures Chapter 3
Graphs Chapter 4
Graphs Chapter 5
Graphs Chapter 6
Graphs Chapter 7
Oxy Permeability
Register of Results
Strength
Summary of Results
Water Sorptivity
Cl Conductivity
Climate Data
Core Strengths
Coring
Correspondance UCT
Curing Method Revised 120d slab
Curing Method Revised 120d wall
Curing Method Revised 28d slab
Curing Method Revised 28d wall
Element Age
Percentage Change with time
Trend to No Cure
w/c ratio
My Computer
Start
Microsoft Word
Exploring -
HP Status Win...
Microsoft


Exploring - Oxy Permeability
File
Edit
View
Go
Favorites
Tools
Help
Back
Up
Cut
Copy
Paste
Undo
Delete
Address
Folders
Chapter 4 Graphs
Climate Regional Evaluation
Climatic Scoring
Slab A1@120days
Slab A1@28days
Slab A2@120days
Slab A2@28days
Slab A3@120days
Slab A3@28days
Slab A4@120days
Slab A4@28days
Slab B1@120days
Slab B2@120days
Slab B2@28days
Slab B3@120days
Slab B3@28days
Slab B4@120days
Slab B4@28days
Slab C1@120days
Slab C2@120days
Slab C2@28days
Slab C3@120days
Slab C3@28days
Slab C4@120days
Slab C4@28days
Wall A@120days
Wall A@28days
Wall B@120days
Wall B@28days
Wall C@120days
Wall C@28days
31 object(s)
My Computer
Start
Microsoft Word
Exploring -
HP Status Win...
Microsoft




File Edit View Go Favorites Tools Help
Back Up Cut Copy Paste Undo Delete
Address
Folders
Register of Results
Strength
Summary of Results
Water Sorptivity
Cl Conductivity
Climate Data
Core Strengths
Coring
Correspondance UCT
Cover Survey
Figures Chapter 3
Finances
Graphs Chapter 4
Graphs Chapter 5
Graphs Chapter 6
Graphs Chapter 7
Mix Design
Oxy Permeability
Register of Results
Oxygen Permeability
Water Sorptivity
4 object(s)
My Computer
Start
Microsoft Word
Exploring - ...
HP Status Win...
08:20
Microsoft


Exploring - Water Sorptivity
File Edit View Go Favorites Tools Help
Back Up Cut Copy Paste Undo Delete
Address
Folders
Water Sorptivity
Chapter 4 Graphs
Climatic Scoring
Slab A1@120days
Slab A1@28 days
Slab A2@120days
Slab A2@28days
Slab A3@120days
Slab A3@28days
Slab A4@120days
Slab A4@28days
Slab B1@120days
Slab B1@28days
Slab B2@120days
Slab B2@28days
Slab B3@120days
Slab B3@28days
Slab B4@120days
Slab B4@28days
Slab C1@120days
Slab C1@28days
Slab C2@120days
Slab C2@28days
Slab C3@120days
Slab C3@28days
Slab C4@120days
Slab C4@28days
Wall A@120days
Wall A@28days
Wall B@120days
Wall B@28days
Wall C@120days
Wall C@28days
33 object(s)
My Computer
Start
Microsoft Word
Exploring - ...
HP Status Win...
08:21
Microsoft